Particle physics at CMS

Marc Weinberg

Particle physics

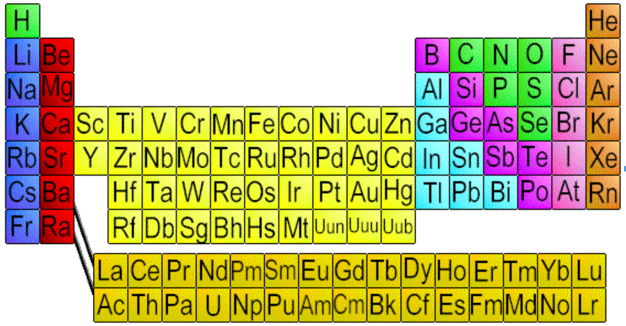
"I offer the modest proposal that our universe is simply one of those things that happen from time to time."

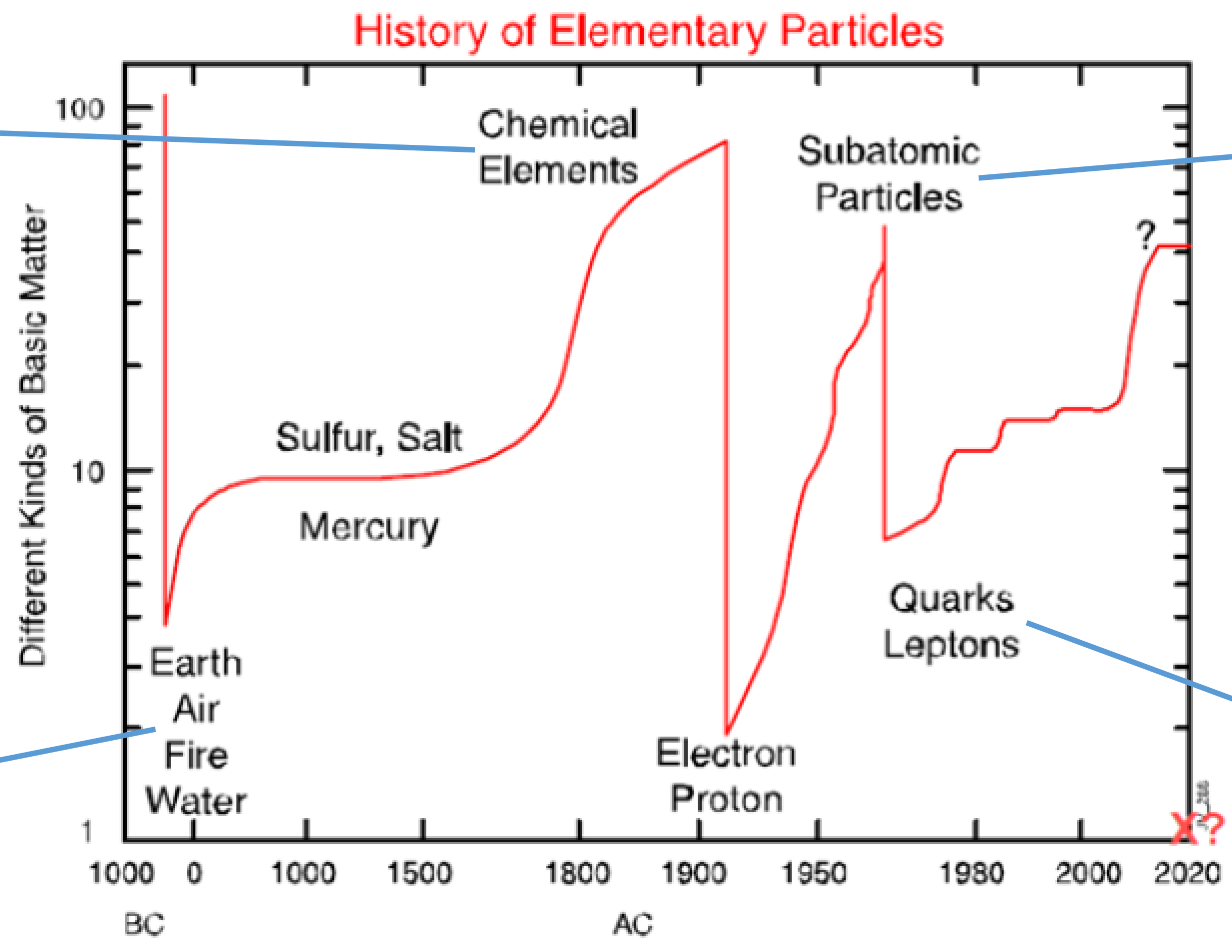
– Edward Tryon

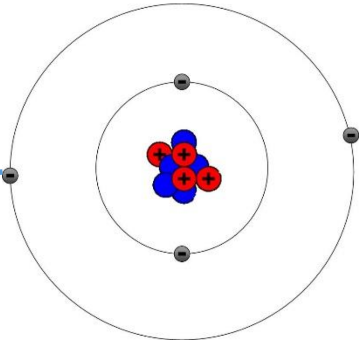
- At its heart, concerns itself with two very fundamental questions:
  - What are the ultimate building blocks of matter?
  - How do these fundamental constituents interact?

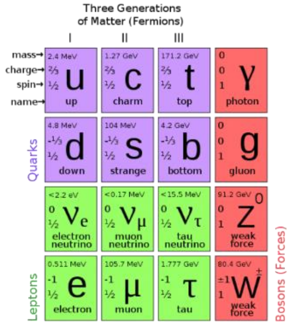
- Kinda started in ancient Greece, but got going for real with John Dalton in early 1800s

Constituents of matter through history



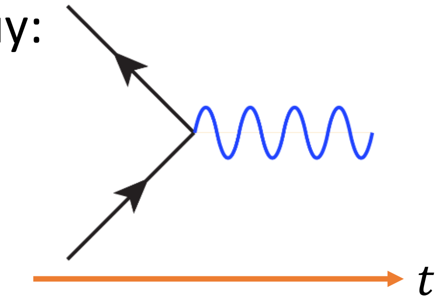






Quantum field theory

All electromagnetism comes down to this guy:



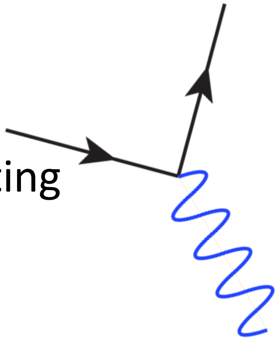
Electron and antielectron (positron) come in and annihilate into a photon

Rules of the game:

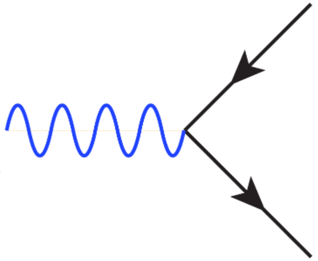
- Time goes to the right (unless you're old, then it goes bottom to top)
- Arrows have to keep going in the same direction
- If the arrow points against the flow of time, it's an antiparticle

A lot of physics processes are really the same process, rotated in time

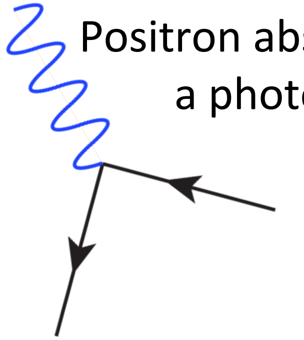
Electron emitting a photon



Photon pair producing

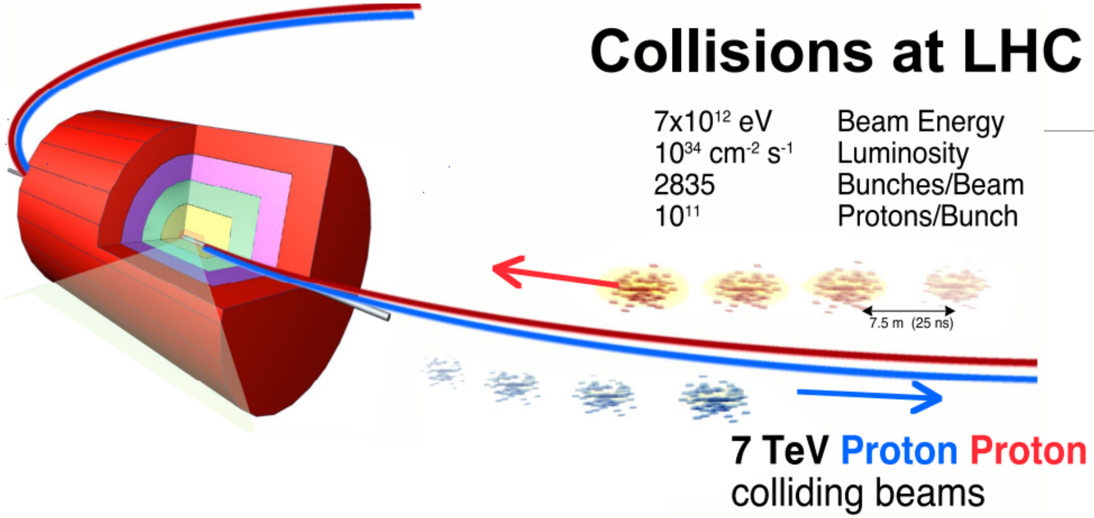


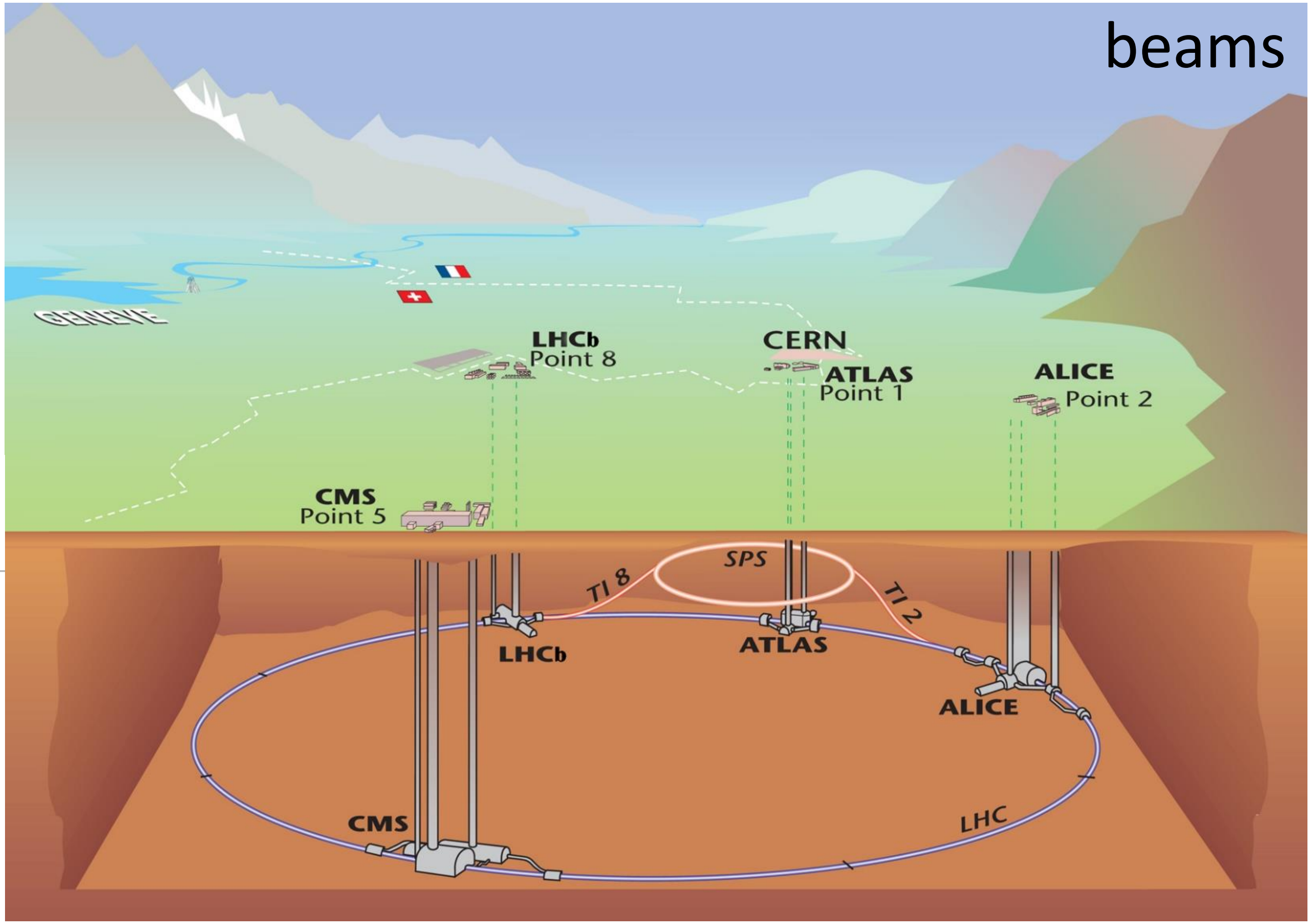
Positron absorbing a photon



The Large Hadron Collider

- Collides two counter-circulating beams of protons
- 40 million head-on collisions per second
- It’s fairly large (C = 27 km)





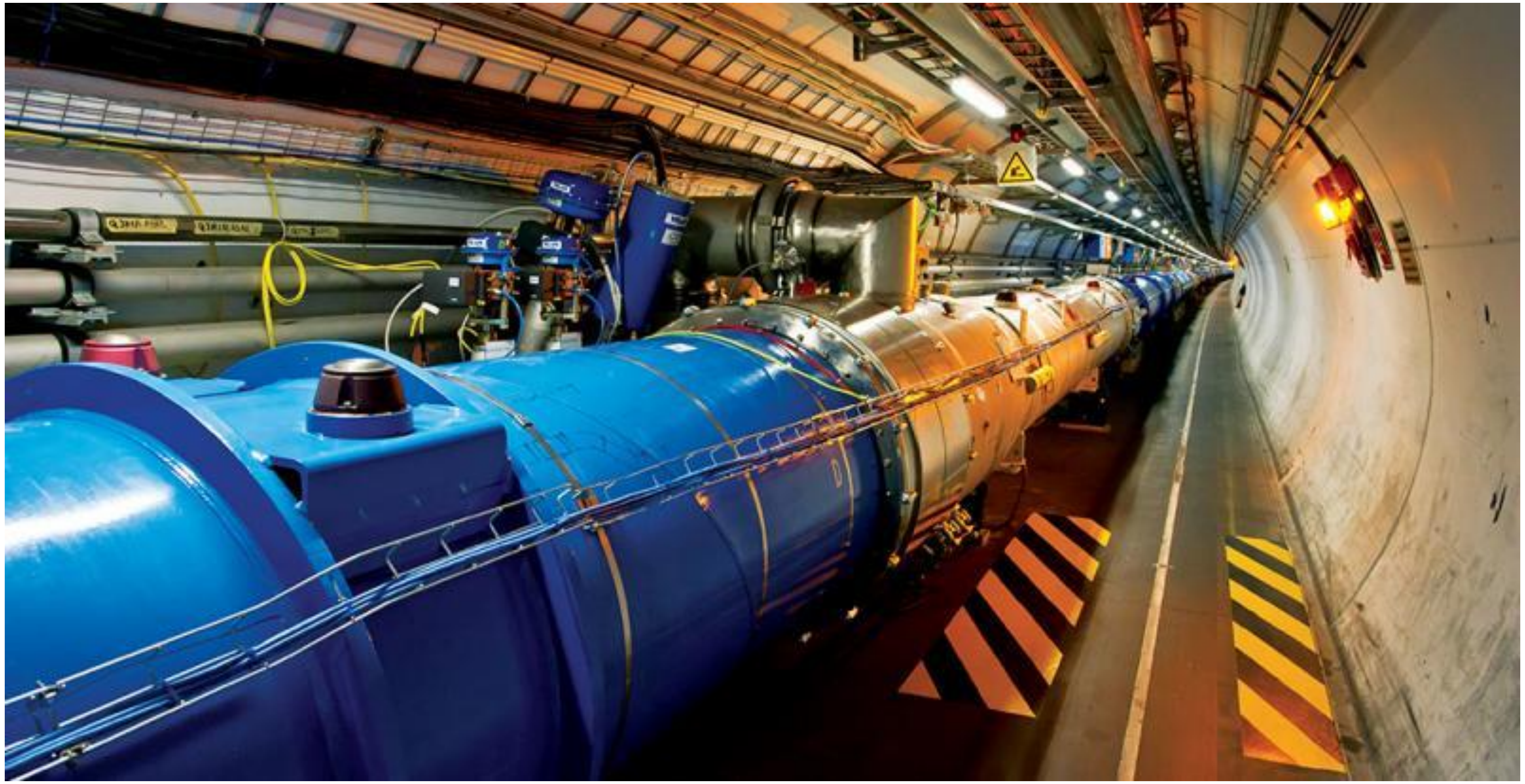
Collisions at the LHC

Luminosity: $10^{34}/cm^2s$ (30x Tevatron)

Energy: 14 TeV (7x Tevatron)

- 8.3 T superconducting dipoles
- 1.9 K operating temperature
- 350 MJoule energy stored in each beam
  - Energy of 400 ton train going at 100 mph

- Over 2000 dipoles
- 100 tons of liquid helium
- 120 MW power consumption

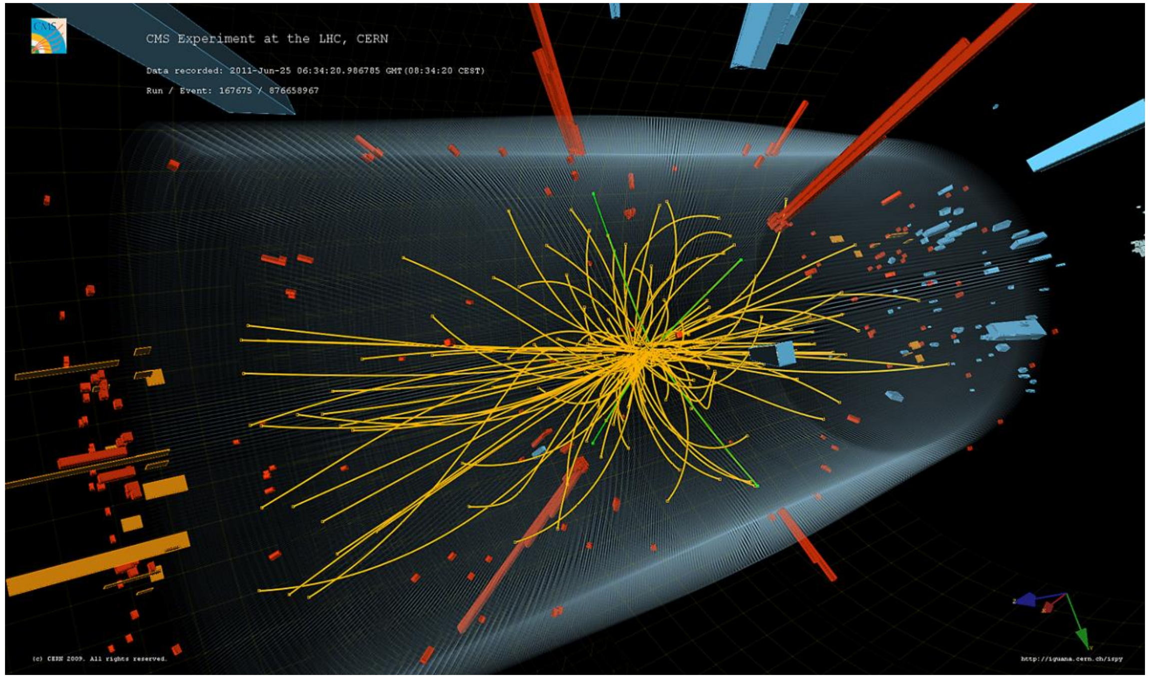


Other neat stuff

- Fairly empty: Pressure in 27 km length vacuum pipes is 10^{-13} atm, lower than on the moon

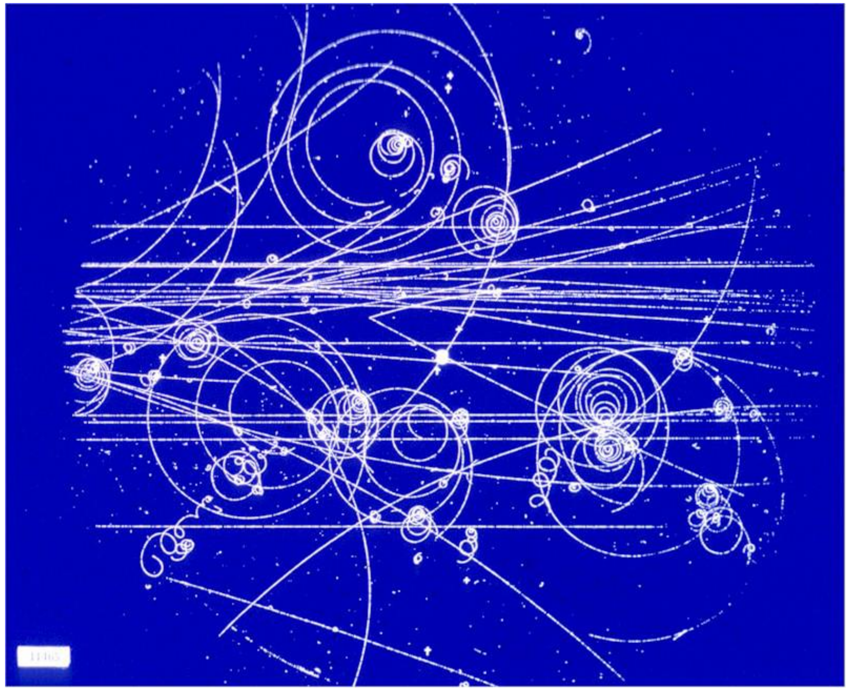
- Fairly cold: Entire length of magnets kept at 1.9 K, colder than deep space, using over 100 tons of liquid helium

- Also pretty hot: Right at collision point, have temperatures ~ 1 billion times hotter than the center of the sun



Particle detection

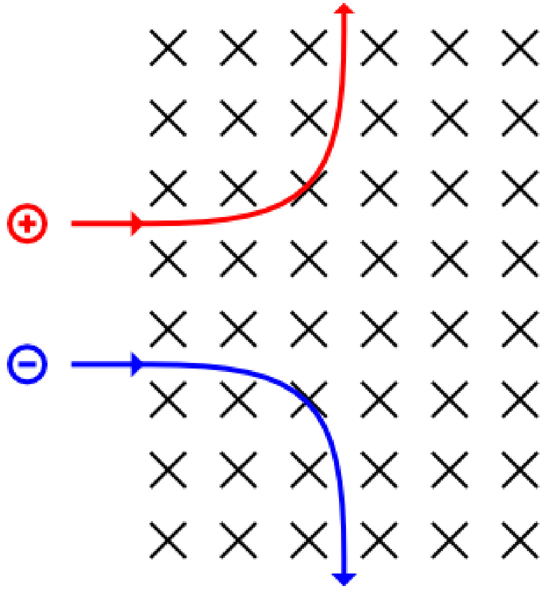
- Can see particles because they interact with matter
- What can we detect?
  - Has to have strong or EM interactions
  - Sufficiently long-lived to make it out of the detector
- Can directly observe:
  - Electrons, muons, photons
  - Neutral and charged hadrons
- Can indirectly observe:
  - Weakly interacting particles (via missing energy)
  - Short-lived particles (from kinematics of decay products)



Particle properties

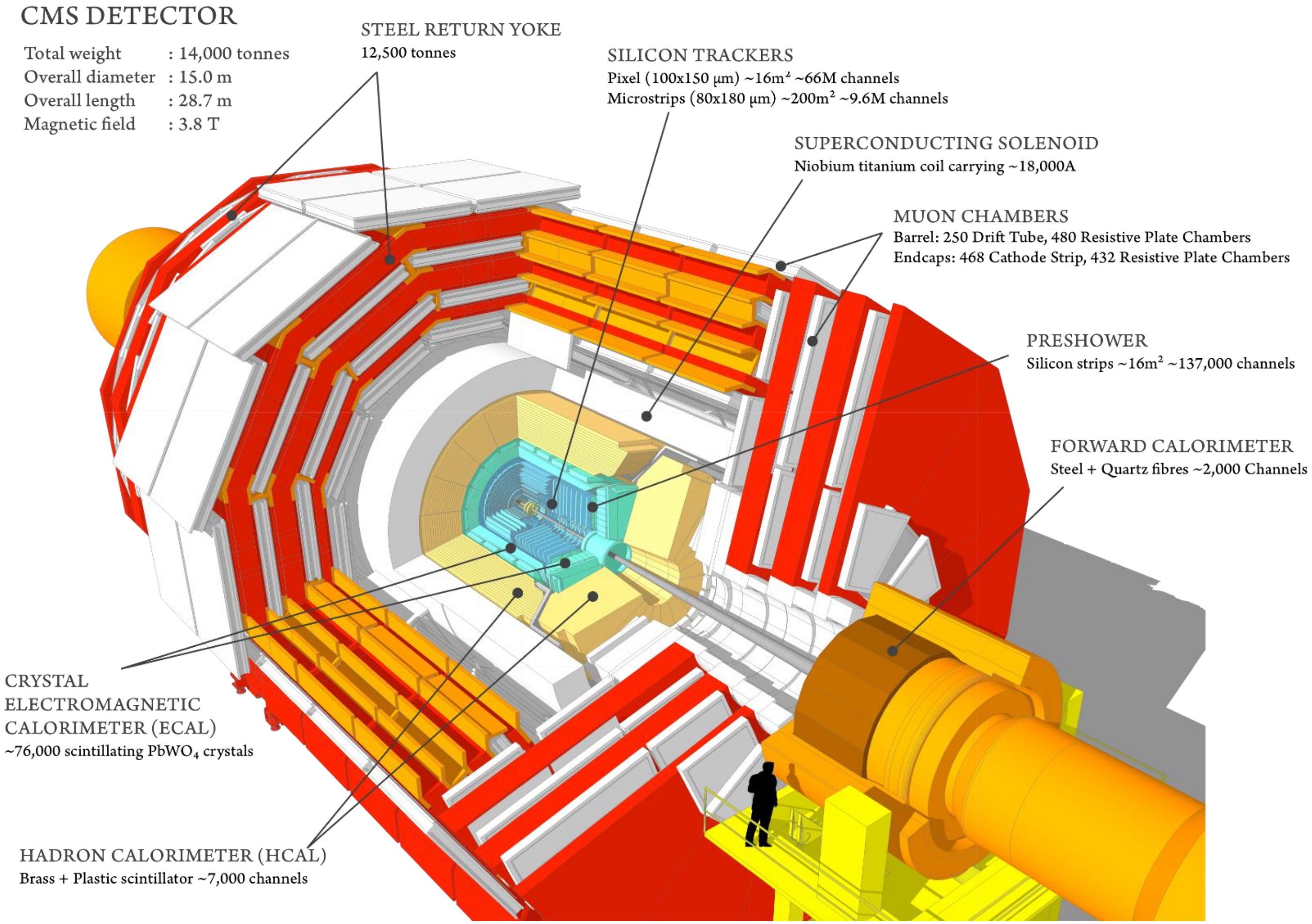
- What properties can we measure?
  - Energy (calorimeter)
  - Momentum (tracking)
    - $F = qvB = \frac{mv^2}{R} \rightarrow p = mv = qBR$
  - Charge (also tracking, using the bend direction)
  - Lifetime (also tracking)
  - Mass
    - $E^2 = p^2 + m^2 \rightarrow m = \sqrt{E^2 - p^2}$

$$\begin{bmatrix} E' \\ p_x' c \\ p_y' c \\ p_z' c \end{bmatrix} = \begin{bmatrix} \gamma E - \beta\gamma p_x c \\ -\beta\gamma E + \gamma p_x c \\ p_y c \\ p_z c \end{bmatrix}$$



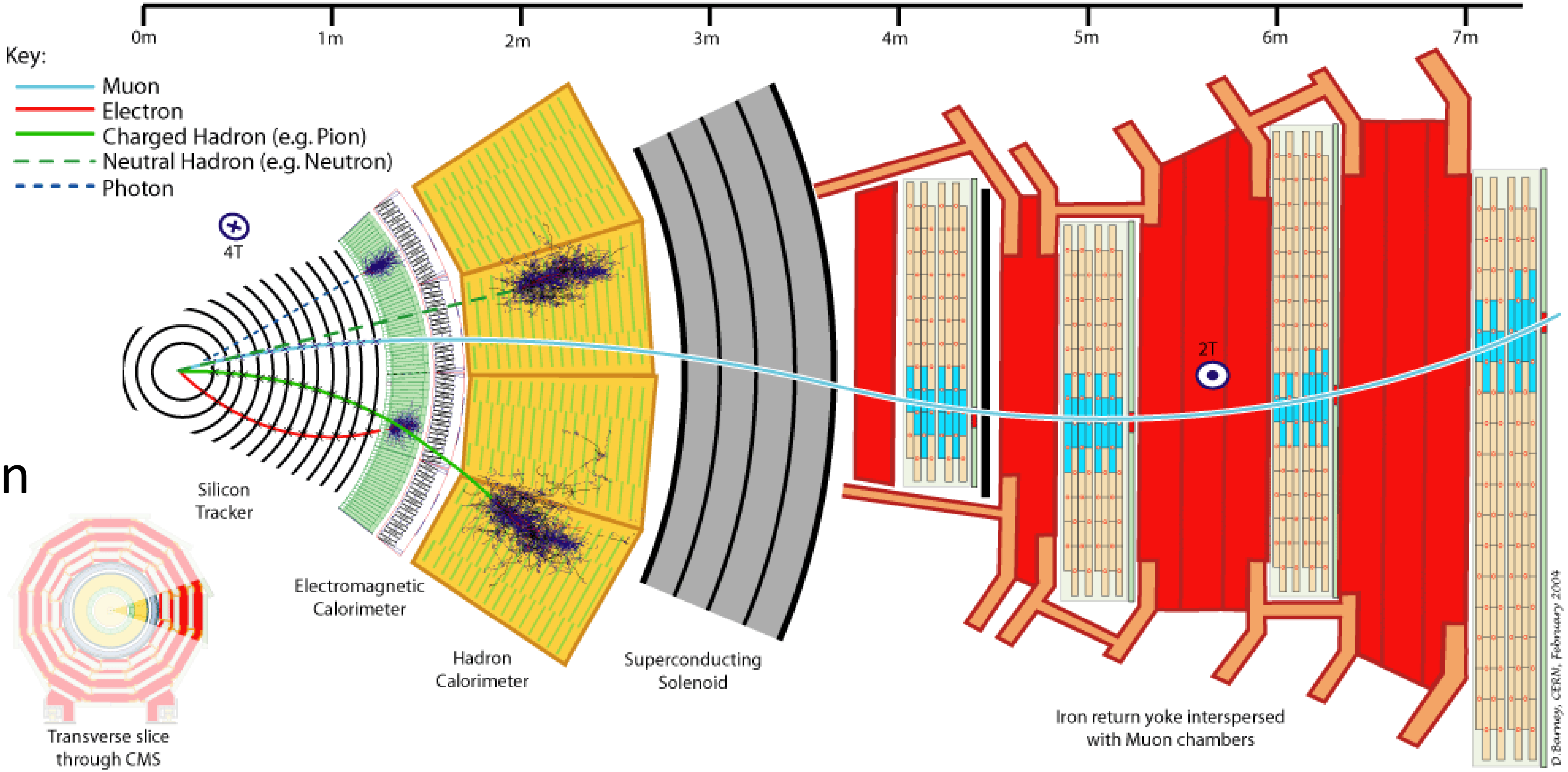
Compact Muon Solenoid (CMS)

- CMS (and ATLAS) are general-purpose detectors
  - Designed to look for whatever new physics might be there
  - Find Higgs and measure properties
  - Find supersymmetry
  - Find whatever other high-energy physics comes along



Layers of CMS

- Like an onion
- Each layer measures the E or p of particles
- Compile measurements in each layer into description of particles



Physics at CMS

Great! So what kinds of physics can we do with this machine?

Lots of different ways to look for new physics

More responsible

Less responsible

- Standard model measurements
- Physics of the Higgs boson
- Searches for Supersymmetry
- Exotic processes and dark matter searches

Physics at CMS

Great! So what kinds of physics can we do with this machine?

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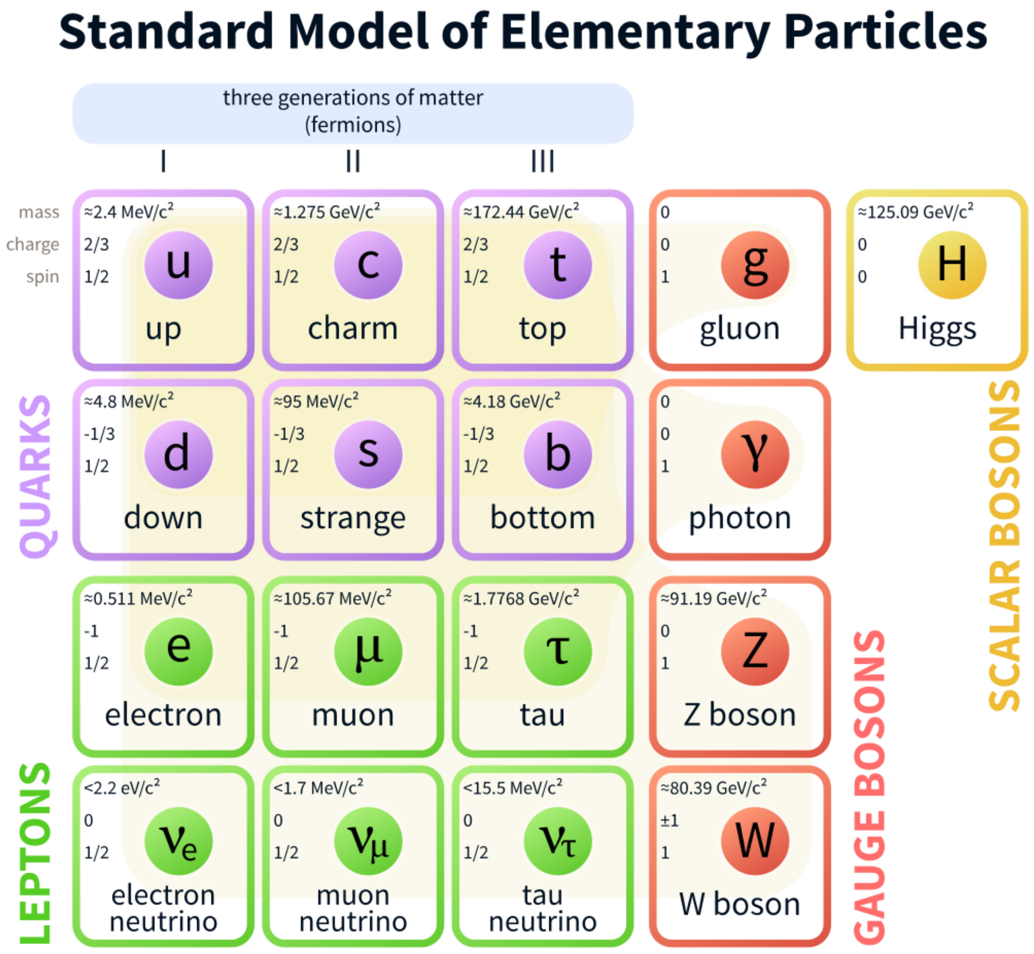
Make careful measurements to find evidence of small deviations

Mostly where I hang out

For the rebels and the dreamers

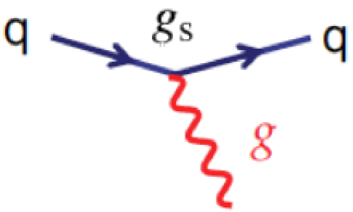
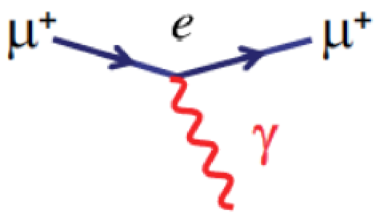
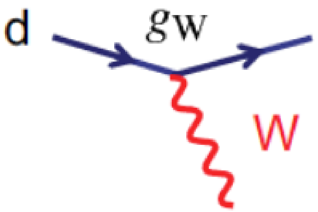
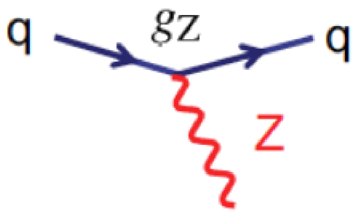
The standard model (SM)

- Crowning achievement of last century of particle physics
- Turns out both matter and forces are particles
- Four fundamental forces
  - Every force gets its own quantum field (except gravity maybe)
- A dozen fundamental particles of matter
  - “Periodic table” with 3 generations
  - Too many? It’s probably fine.



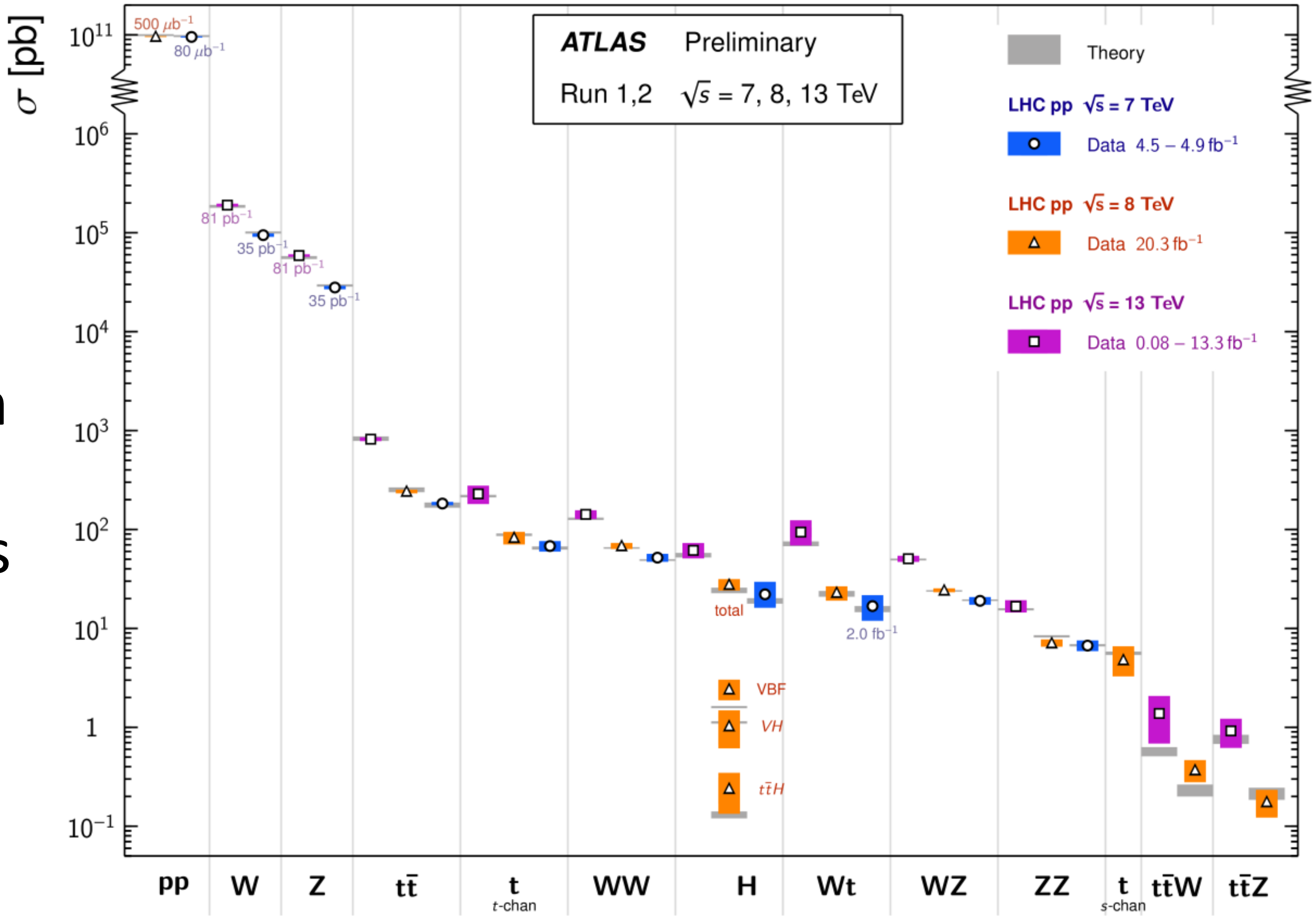
Fundamental interactions

- Interactions are (irritatingly) well described by the SM

STRONG	EM	WEAK CC	WEAK NC
			
Only quarks	All charged fermions	All fermions	All fermions
Never changes flavour	Never changes flavour	Always changes flavour	Never changes flavour
$\alpha_S \sim 1$	$\alpha \simeq 1/137$	$\alpha_{W/Z} \sim 1/40$	
Gluons massless	Photon massless	W+, W- very massive	Z^0 very massive

Spectacular confirmation of SM

Measurements of the production cross sections of various processes

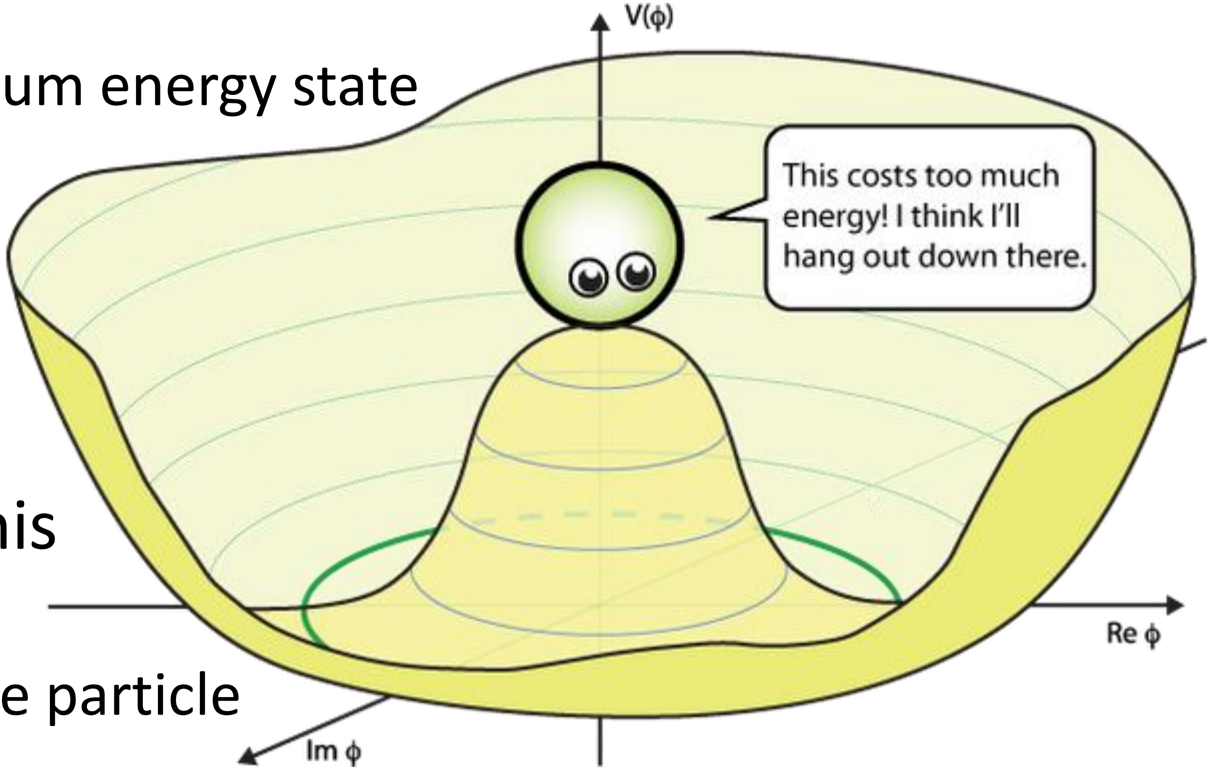


Something's missing…

- From Emmy Noether: Any continuous symmetry of a system corresponds to some conserved quantity
  - Symmetry under time translations results in energy conservation
  - Symmetry under space translations results in momentum conservation
  - In field theory, conserved charges come from a symmetry called gauge invariance
- Oops! Only get gauge invariance if all the particles are massless and move at the speed of light
  - Mass terms spoil the invariance
  - Super embarrassing, since most of them do have mass

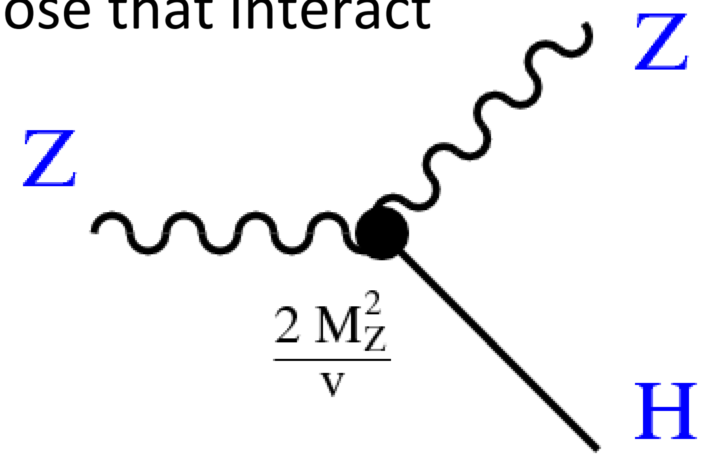
The Higgs Mechanism

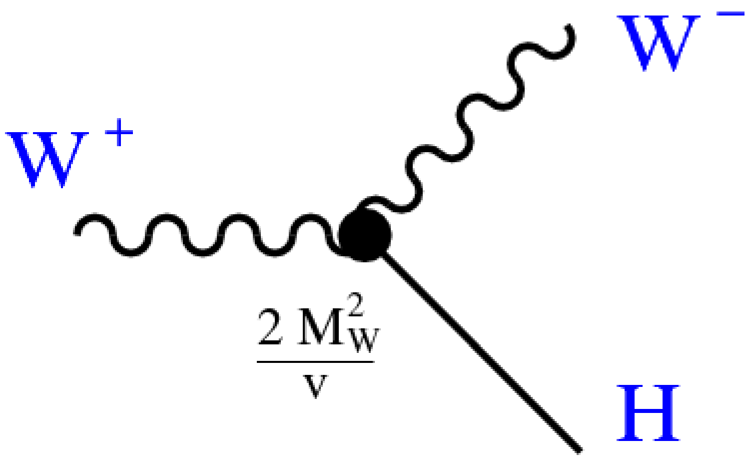
- What if there's a new field out there that makes a "Mexican hat" potential
- No mass term in the root equation because it corresponds to the origin point
  - At the origin, particles are massless
  - When particles see this potential, the minimum energy state is to hang out along the green circle
  - Called "electroweak symmetry breaking"
- The W and Z bosons get mass from this mechanism
- Any particle that interacts directly with this field will also pick up a mass
  - The greater the interaction, the "heavier" the particle



The Higgs boson

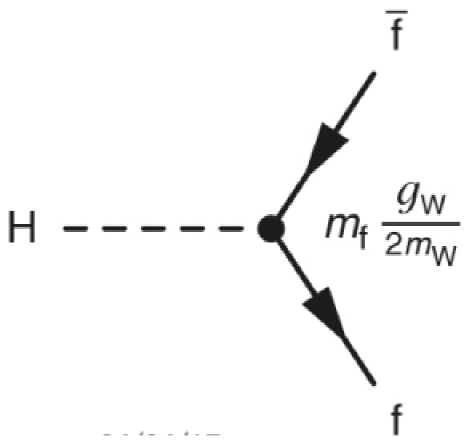
- Funny story, the Higgs boson wasn't actually mentioned until long after the mechanism was proposed
  - Higgs boson is an excitation of the Higgs field, the same way the photon is an excitation of the EM field
  - Higgs field can interact with itself, so the Higgs boson has mass!
- The coupling strength is directly related to the mass of the particle
  - Heavier particles are those that interact more with the Higgs

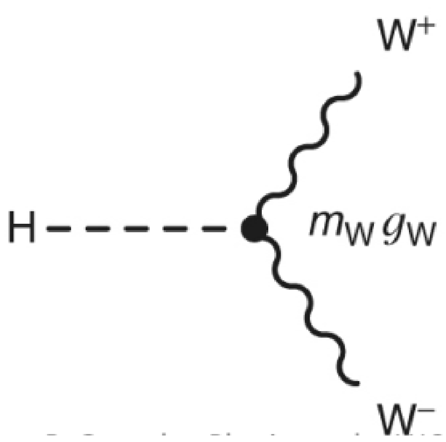


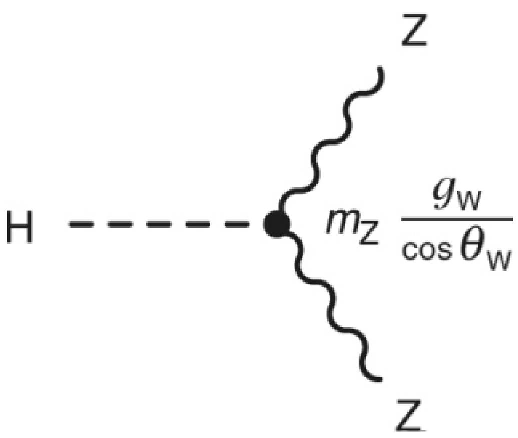


Finding the Higgs

- Remember from earlier: We can always rotate the process in time
  - The Higgs interacts more with heavier particles
  - So a Higgs cruising along is more likely to decay into heavier particles than light ones!
- No coincidence that the best channels to observe the Higgs are from the five heaviest particles (except that last one…):
  - H → ZZ
  - H → W^+W^-
  - H → $b\bar{b}$
  - H → $\tau\bar{\tau}$
  - H → $\gamma\gamma$ (???)

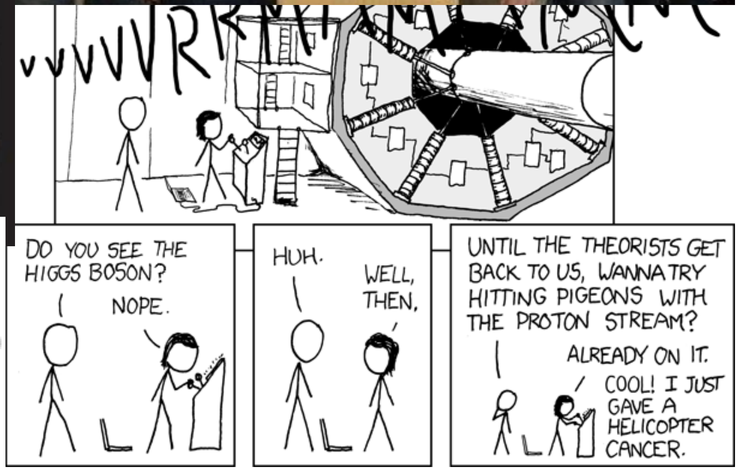






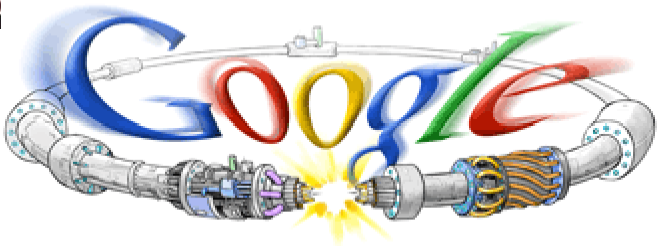
Getting in the news for finding the Higgs

You know, whatever, NBD



This may be the last thing you ever read: Large Hadron Collider fires up in minutes

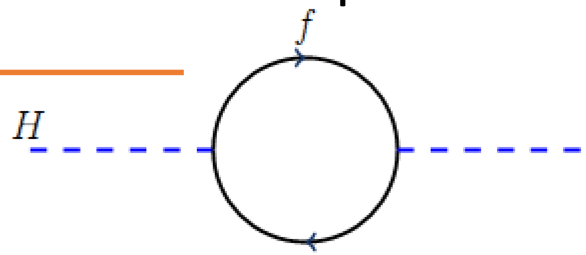
By Andrew D. Smith / Guest blogger
adsmith74@gmail.com | Bio
2:12 AM on Wed., Sep. 10, 2008 | Permalink



But now another problem

- Hierarchy problem: Why is the Higgs mass what it is?
- According to field theory, base Higgs mass should be ~ 100 GeV
  - But the mass should *also* get corrections from loops of “virtual” particles:

$$m_H^2 = (m_H^2)_0 - \frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots$$



- We can interpret Λ_{UV}^2 as the energy where new physics comes along and changes the situation
  - No particular reason Λ_{UV}^2 couldn’t be enormous, like the Planck scale (10^{19} GeV)
  - So how do all these gigantic corrections miraculously cancel each other out to keep the Higgs mass to 125 GeV?

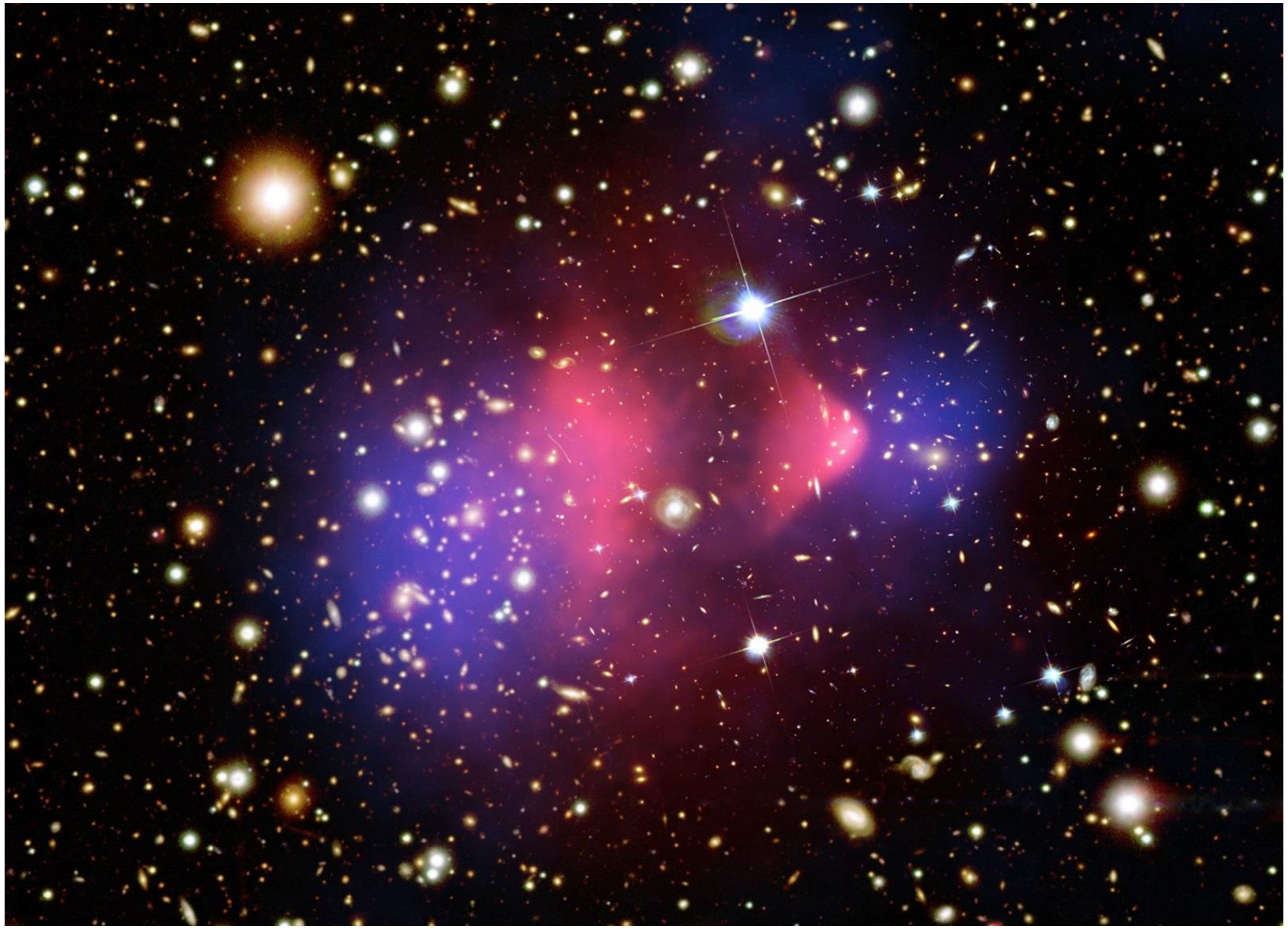
And… yet another problem

- While we're on the subject, dark matter… what is it?
  - Doesn't interact electromagnetically
  - Does interact gravitationally

All SM particles have been excluded as possible dark matter candidates

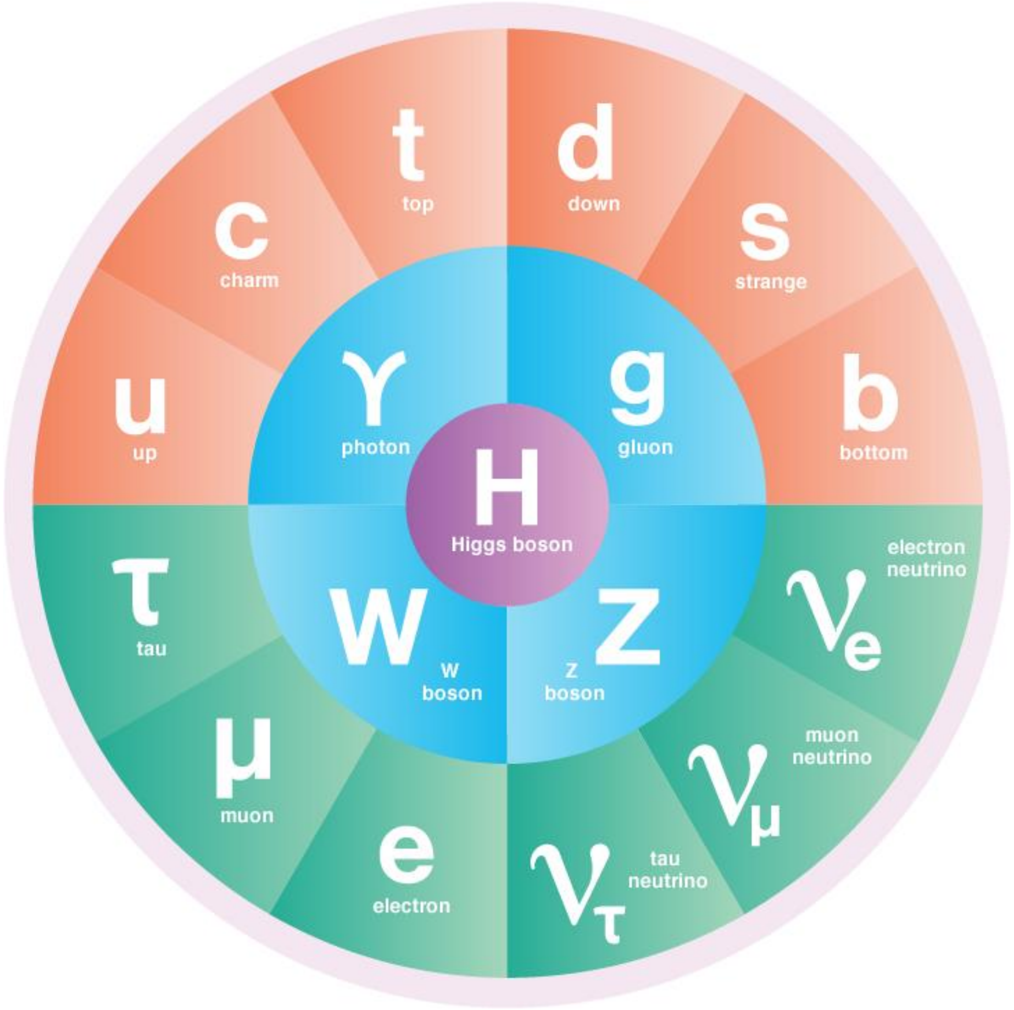
Red: Baryonic matter (from X-rays)

Blue: Total mass (from gravitational lensing)



Quick question

- Here's the SM in circle form (since why not)
- All the matter particles are on the outside, all the force particles are on the inside



What determines where a particle goes?

> That is, if you discover a new particle tomorrow, do you put it in the outside ring, or the inside ring?

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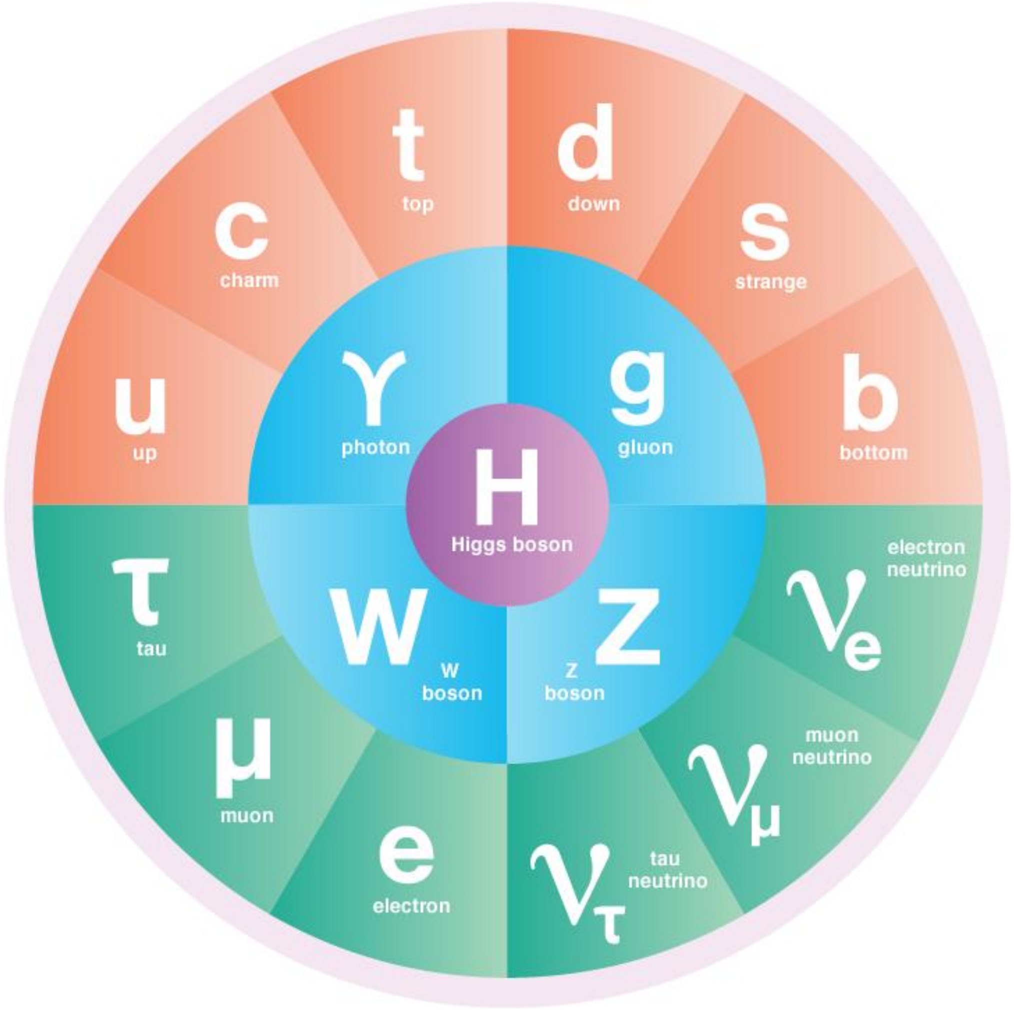


What determines where a particle goes?

That is, if you discover a new particle tomorrow, do you put it in the outside ring, or the inside ring?

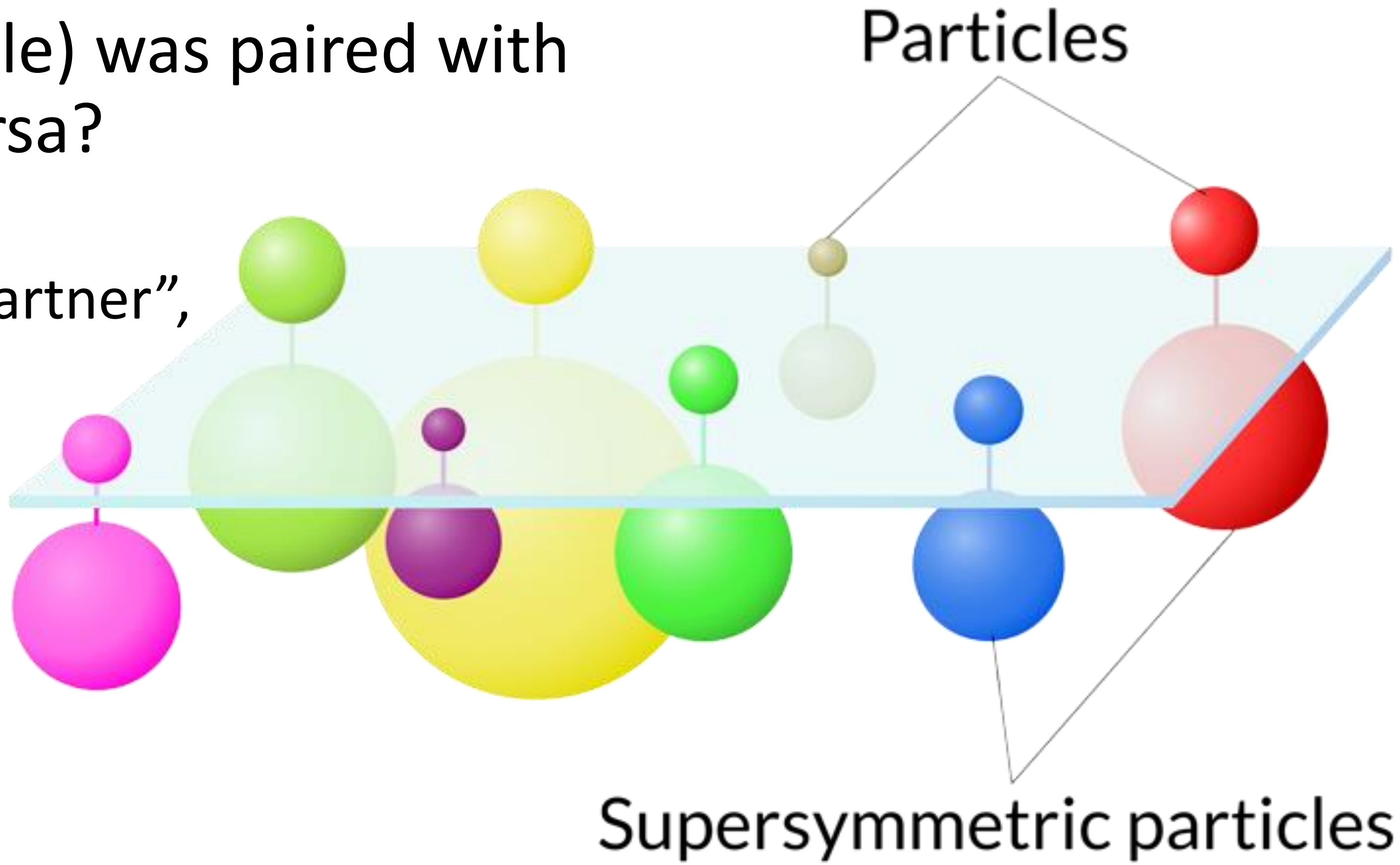
Spin! The difference between matter (fermions) and forces (bosons) is a half-unit of spin

Supersymmetry (SUSY)

What if each fermion (matter particle) was paired with a boson (force particle) and vice versa?

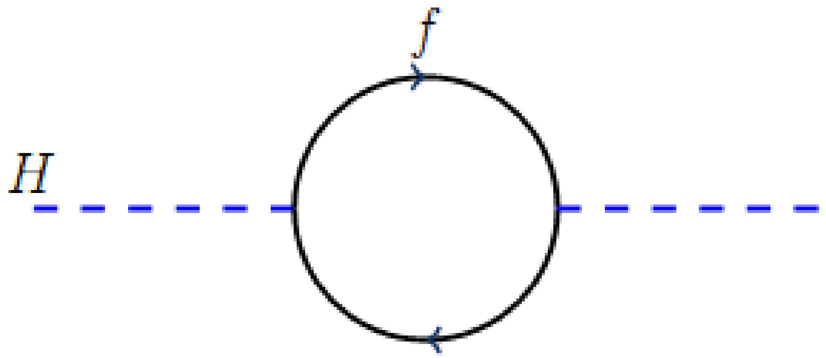
Maybe every SM particle has “superpartner”, not yet discovered

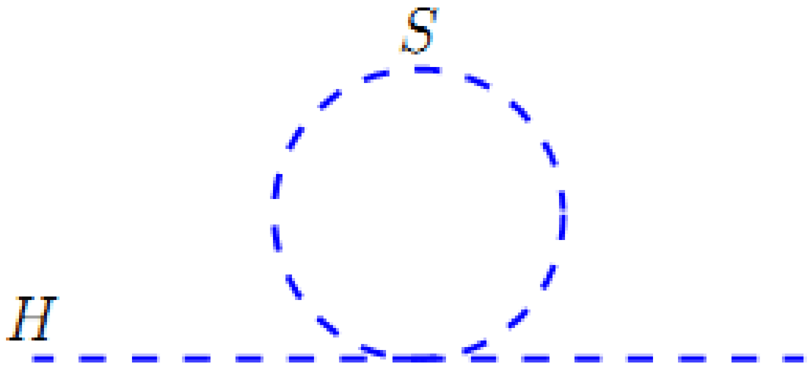
New particles have higher masses
→ SUSY must be broken symmetry



SUSY and the Higgs mass

- Now we get another loop diagram from a boson corresponding to each SM fermion





$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots \qquad \Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\Lambda_{UV}^2 + \cdots$$

- Voila! Corresponding correction with opposite sign from new particles
  - Each SM particle gets a partner to cancel it out
  - We can interpret Λ_{UV} as the mass scale of the new particles (needs to be ~ 1—2 TeV)

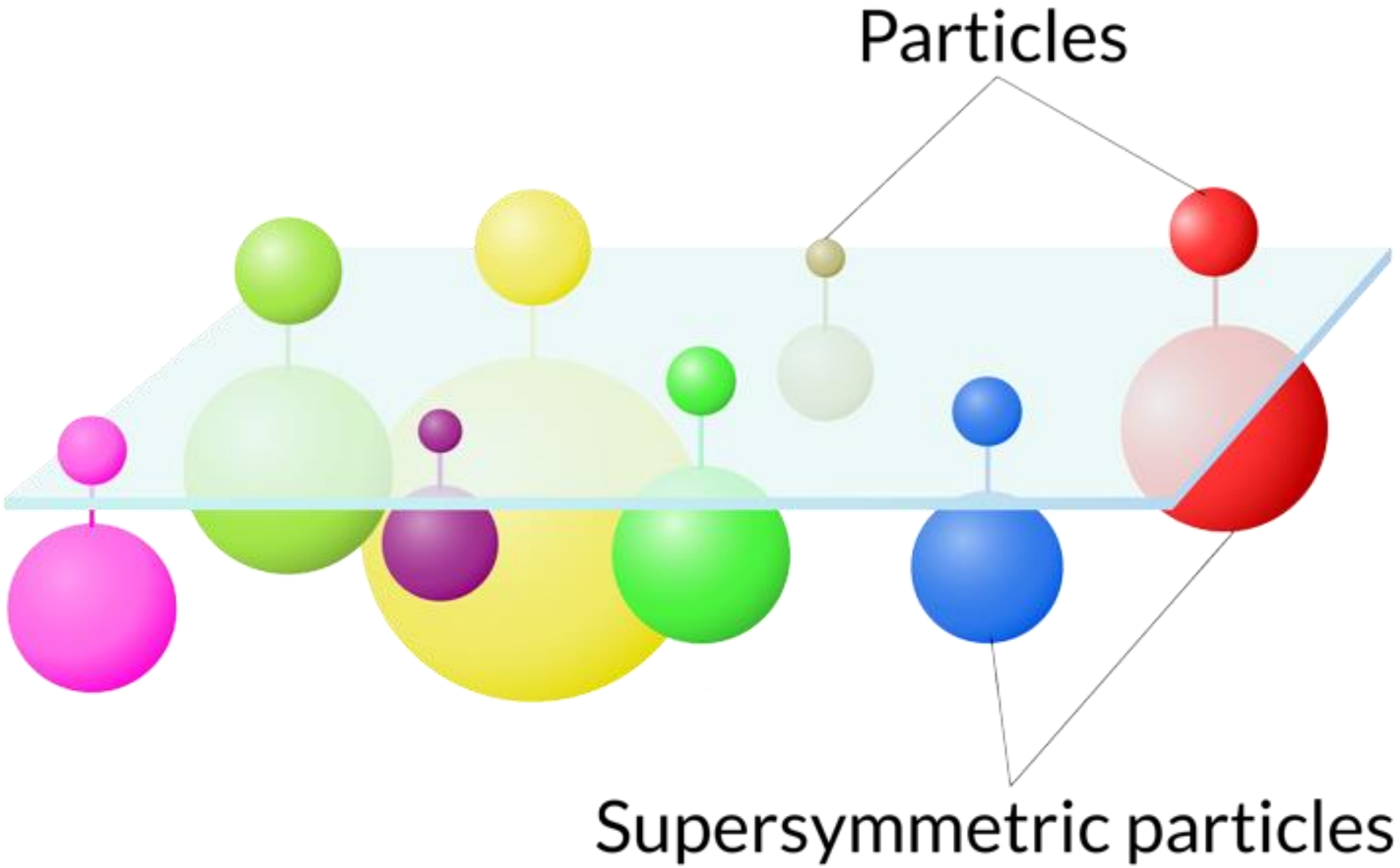
More SUSY

Small wrinkle: New particles would let protons decay... which they don't

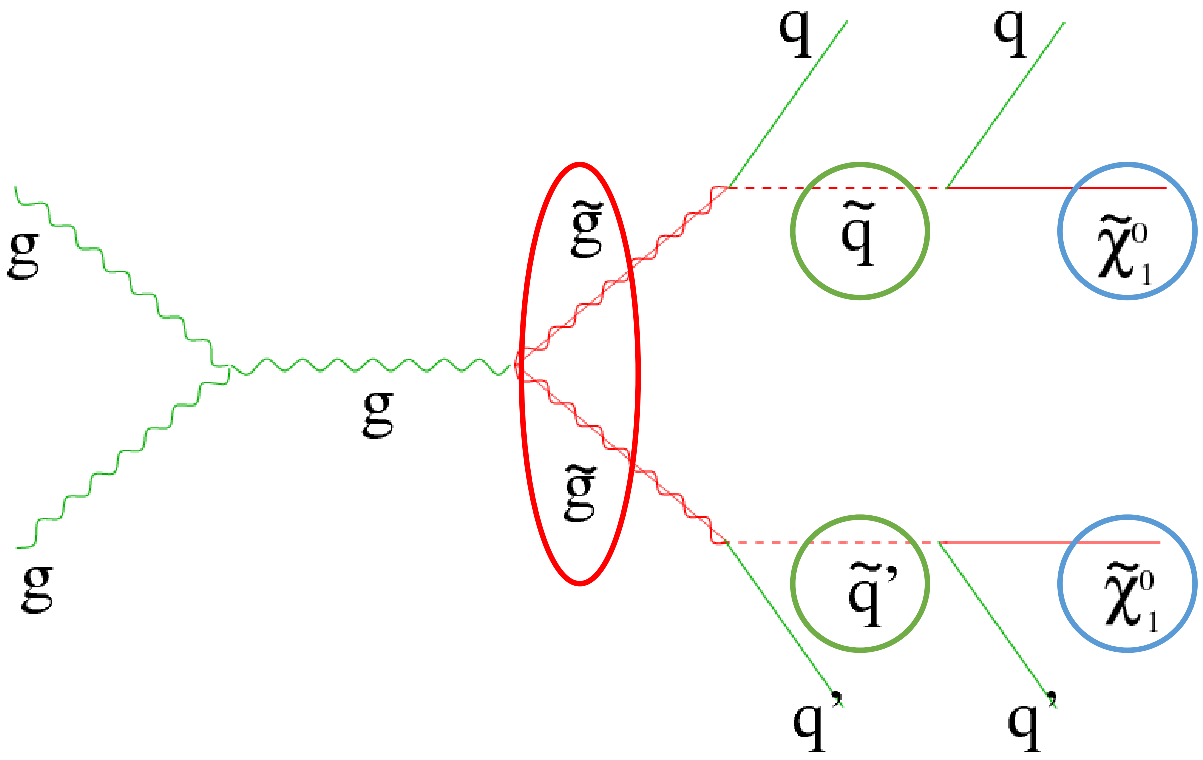
Toss in new number, "R-parity"

All SM particles have R = +1, all superpartners have R = -1

Rule: Product of all incoming stuff equals product of all outgoing stuff



Interesting consequences of SUSY



1. You always have to make SUSY particles in pairs

2. If a SUSY particle decays, it has to go to another SUSY particle

3. The lightest SUSY particle (LSP) is completely stable

Could dark matter be SUSY stuff?

So the lightest SUSY particle (LSP) is

- Heavy
- Neutral
- Weakly-interacting
- Completely stable

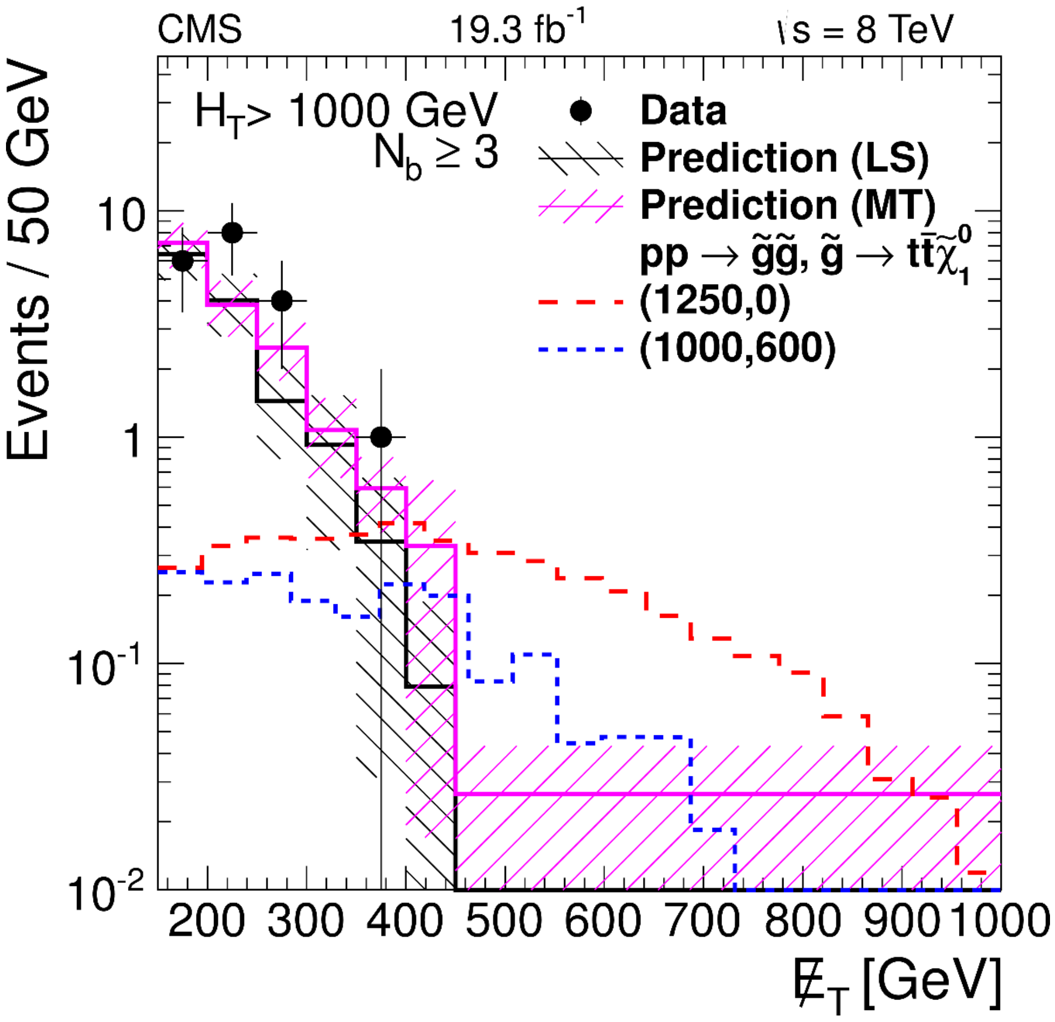
Makes an ideal dark matter candidate!

How do we look for SUSY?

- The LSP typically carries away a lot of invisible energy

- Resulting SUSY signatures: Hadronic stuff + missing energy (+ maybe other stuff)

- So we might well see dark matter in our detectors before we identify it in space

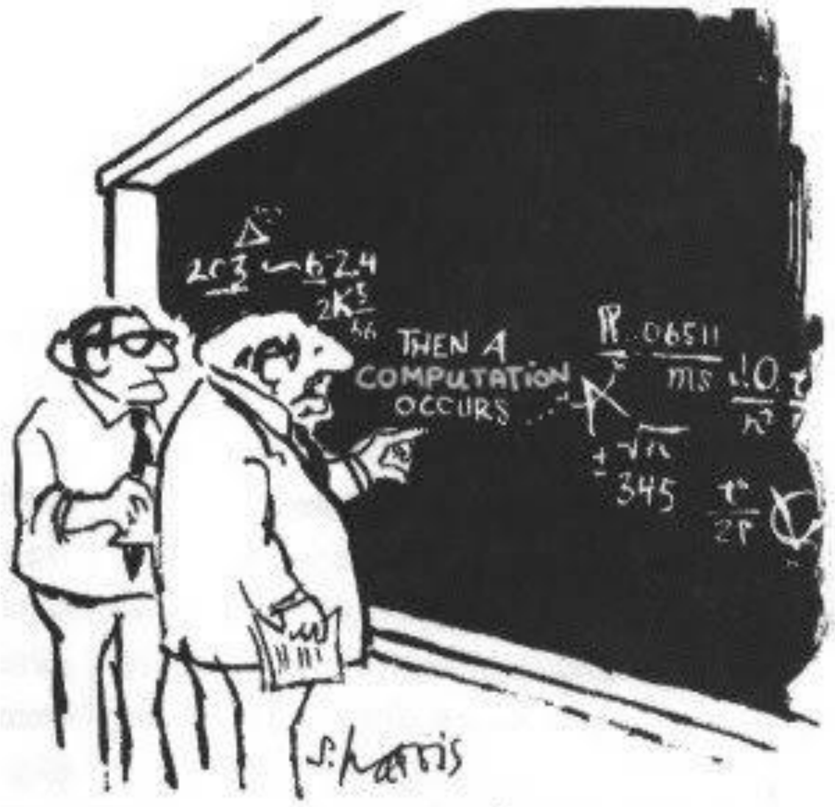


Even more exotic physics

SUSY is just one of many new physics models that could show up at the LHC

- Extra dimensions
- Extended Higgs sector
- Grand unified theories
- Leptoquarks
- New heavy gauge bosons
- Compositeness

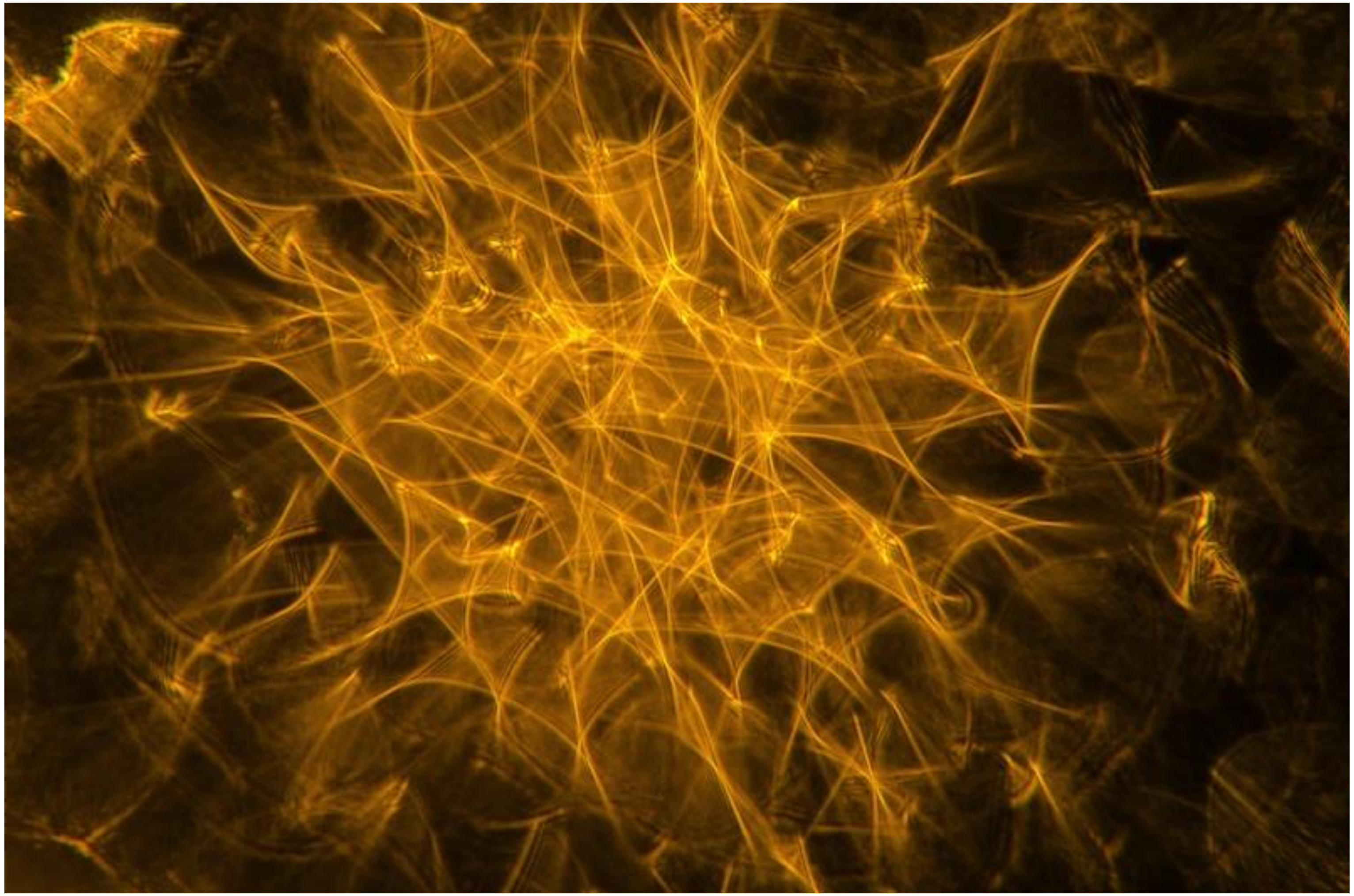
Any of this might be found, if we have folks brave enough to look



"good call using a computer here in step two."

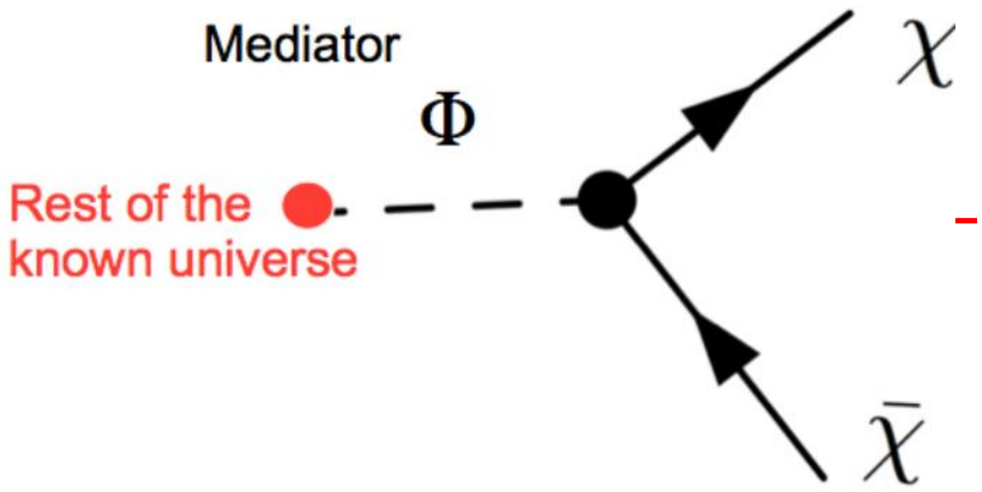
Dark matter, dark energy

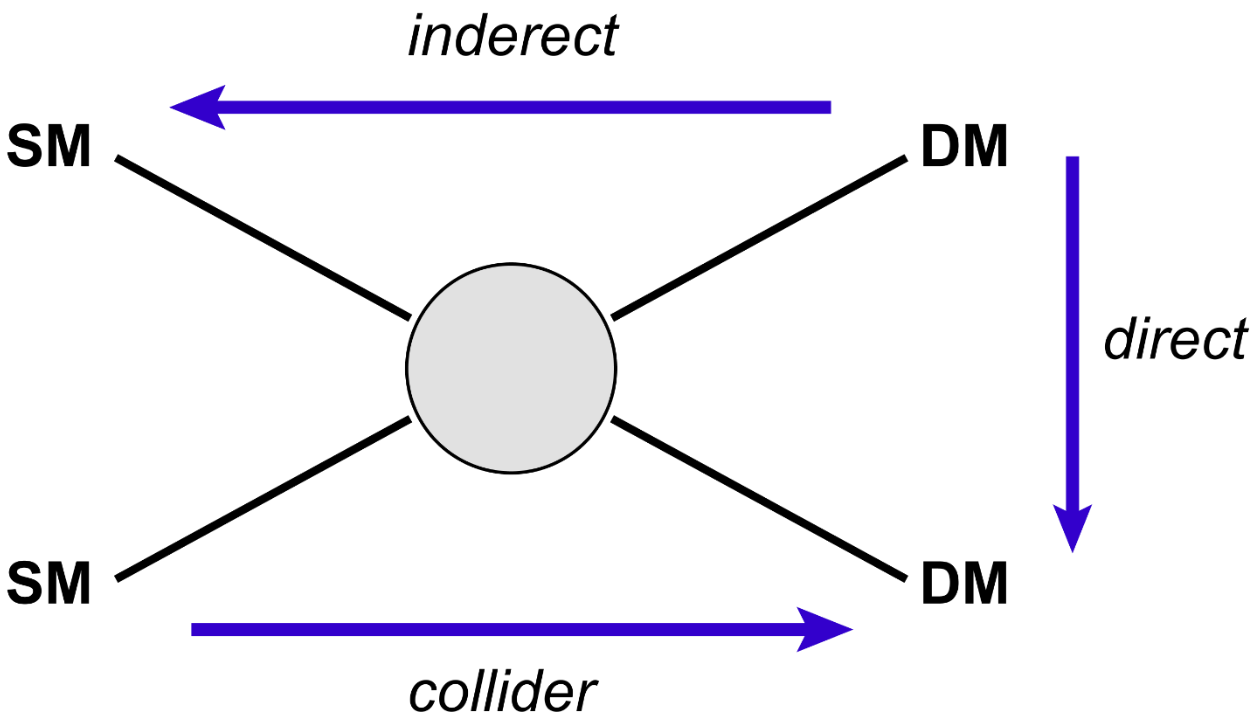
- We've talked about SUSY, but there are a lot of other things dark matter could be
  - Extra-dimensional WIMPs
  - Sterile neutrinos
  - Axions
  - Dark photons
  - Mirror world particles



How do we look for dark matter?

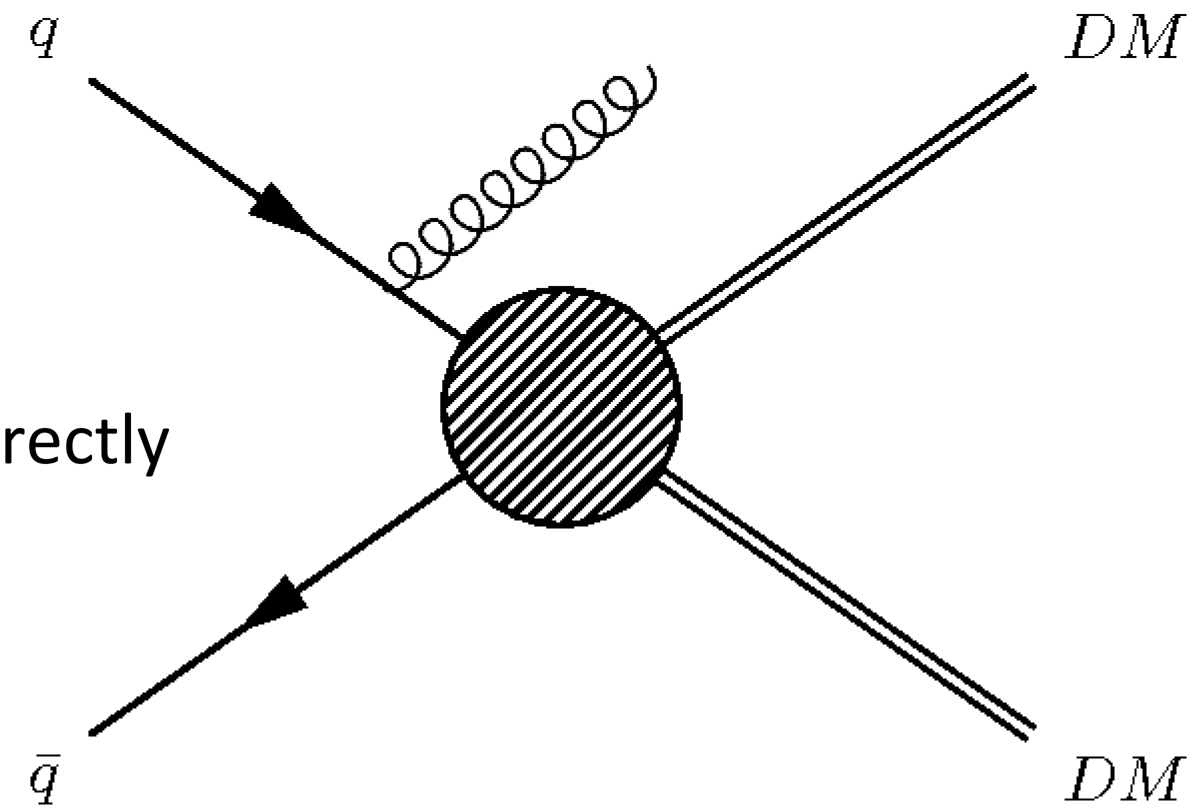
- Depends a lot on how it interacts with the universe
- Typically assume some mediator particle
  - Yields pairs of DM particles





Mono-X searches

- Produce it through a mediator
  - Need something else in the event to flag it
- Searches better for migher-mass mediators
- CMS not really designed to look for DM directly
  - Rely on accidental initial radiation
  - Looks like something + missing energy



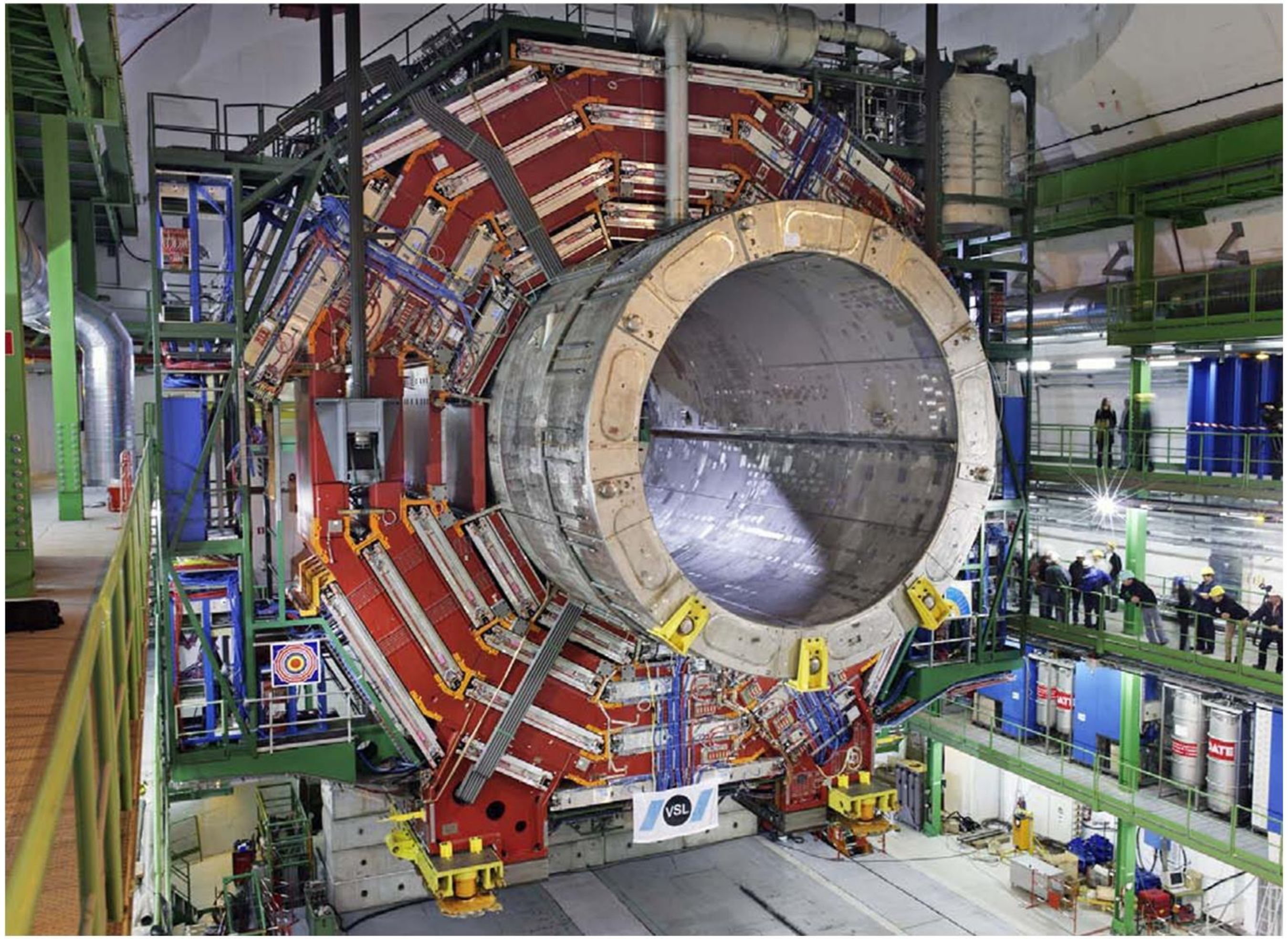
Next steps?

- SM is pretty good; answers a lot of questions about the universe. But so many unanswered questions are still out there!
  - Why do we observe matter and not antimatter, if we almost always make them (and destroy them) in pairs?
  - What is dark matter? What is dark energy?
  - Are quarks and leptons fundamental, or is there even smaller stuff?
  - Why are there three generations of matter? Why do the particles have the masses they do?
- Any (or all!) of these questions could be answered by the LHC
- We have beautifully wrapped up the physics of the 20th century. The *next* thing we find will be the beginning of the physics of the 21st centure

Backup

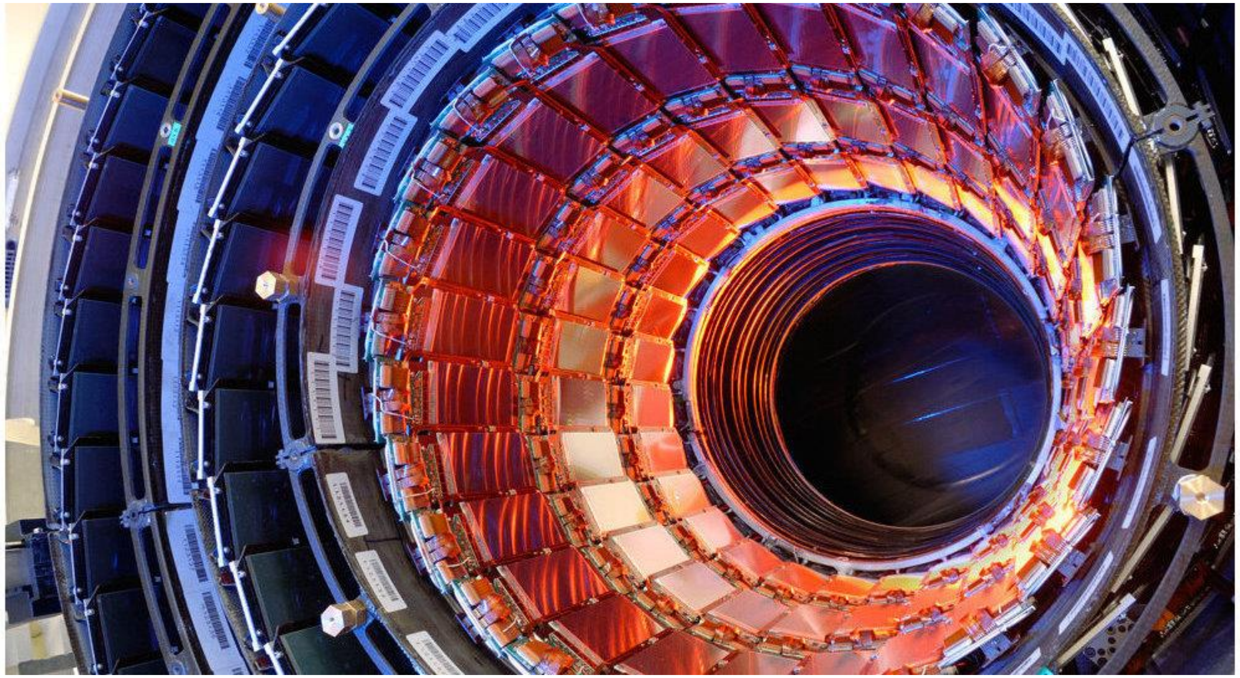
Superconducting solenoid

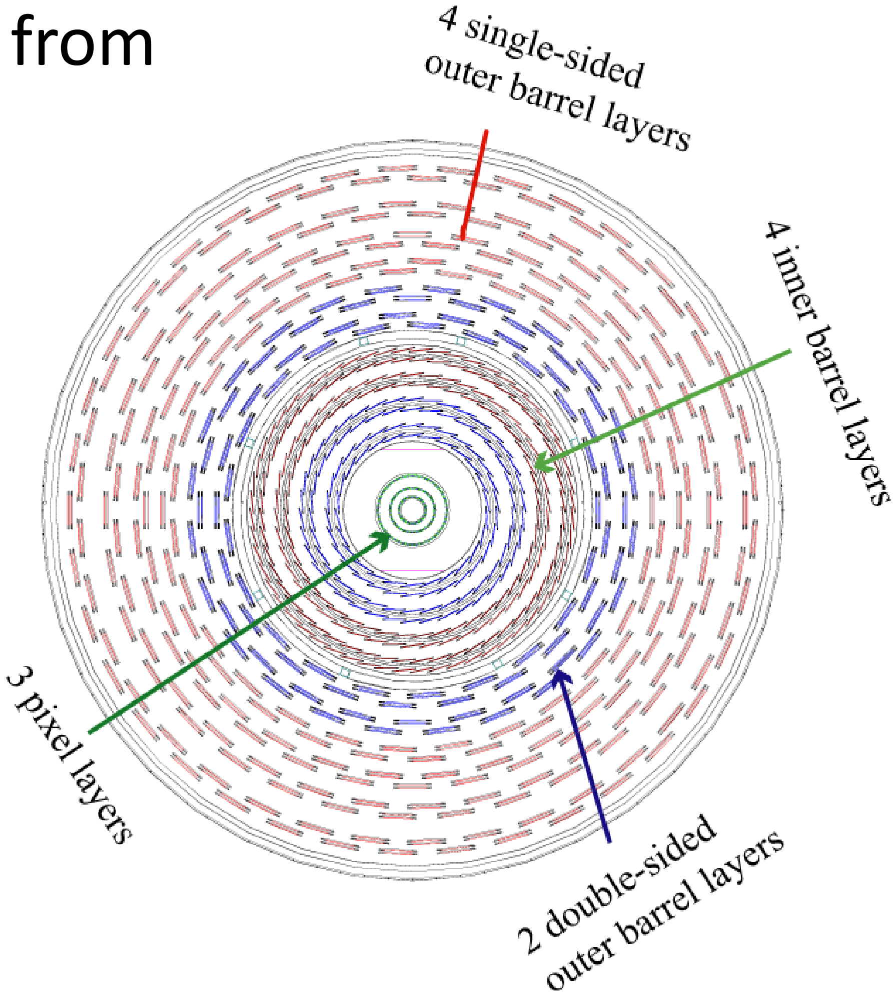
- Main feature of CMS: 3.8 T solenoid
- Want a big ol' magnet to make charged particles bend
  - Bigger the magnet, better the momentum resolution
  - CMS is "compact" because we made the magnet so large we could fit the calorimeters inside



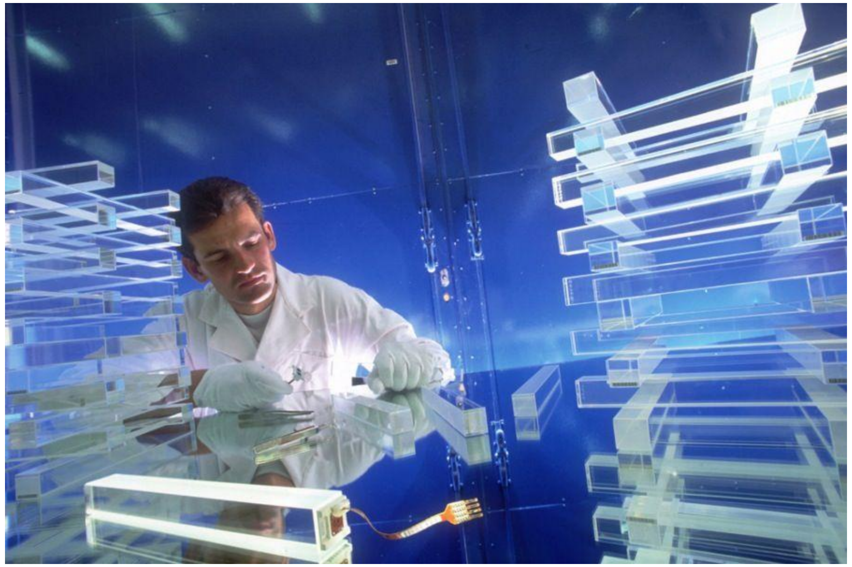
Silicon tracker

- Reconstruct trajectories of all the charged particles from collisions
- 214 m2 silicon, 65.9 M silicon pixels, 11.4 M silicon strips





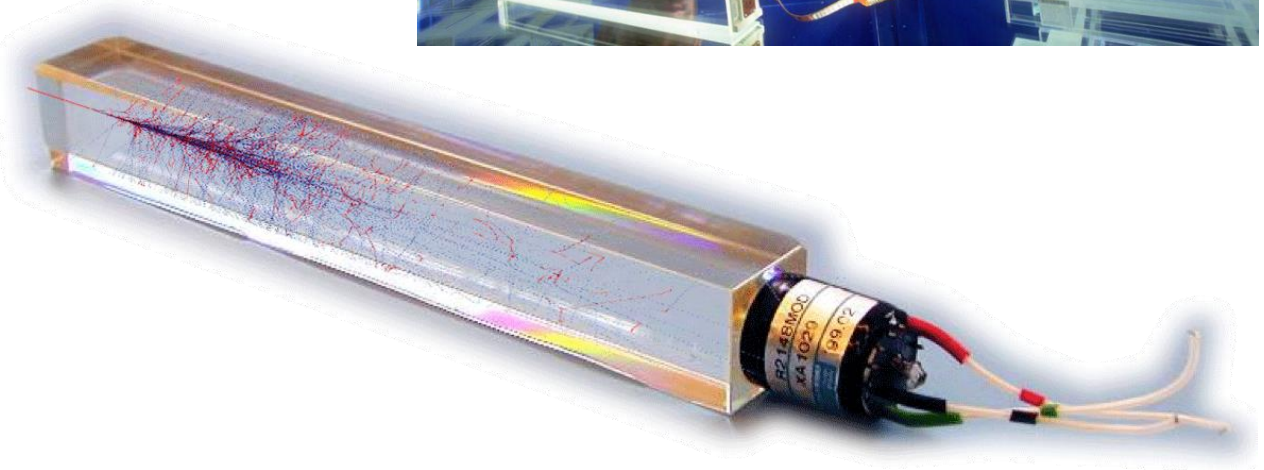
Electromagnetic calorimeter (ECAL)



- For detecting electrons and photons
- Made of ~ 76K crystals of lead tungstate ($PbWO_4$)

Great stuff. Want something:

- Heavy (so particles interact with it a lot)
- Transparent (so you can collect the light at the end)

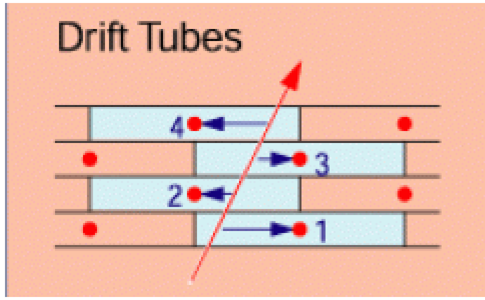


Hadronic calorimeter (HCAL)

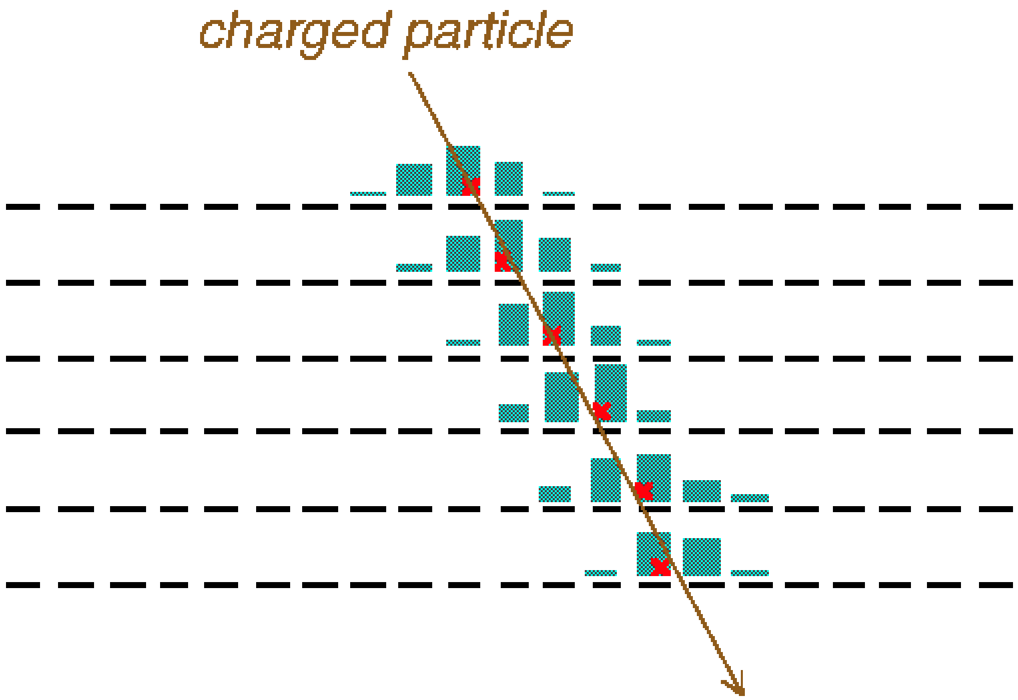
- For detecting hadrons
  - Protons, neutrons, pions, kaons, etc.
- Made of alternating layers of plastic scintillator and brass (or quartz and steel)
- Designed to sample the shower a particle makes
  - Work backwards to figure out energy

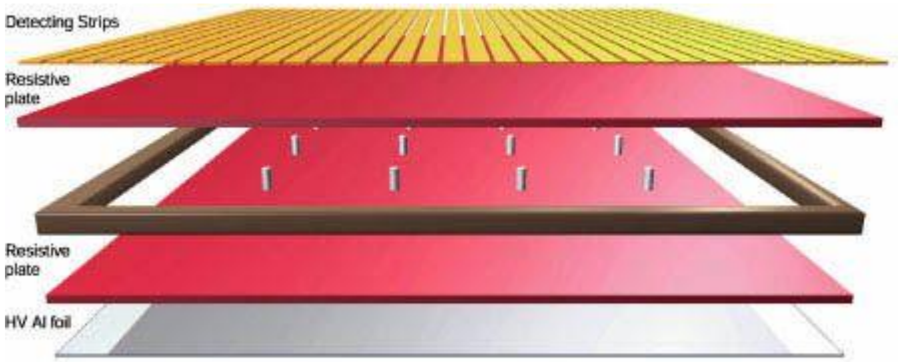
Muon detectors

- Three different types of detectors
  - For redundancy (also to make everyone happy)



- Muons are typically very penetrating
  - Stick the detectors in giant hunks of iron so nothing else gets through





H →γγ decay

- Comes from $H \to t\bar{t}$
  - But the Higgs weighs ~ 125 GeV, and the top quarks weigh 172 GeV *each*
  - Not enough energy! Instead make *virtual* tops